Fundamental Research in High Energy Density Science (2023)

DETAILS

130 pages | 7 x 10 | PAPERBACK
ISBN 978-0-309-69414-8 | DOI 10.17226/26728

CONTRIBUTORS

Committee on the Assessment of High Energy Density Science; Board on Physics and Astronomy; Division on Engineering and Physical Sciences; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2023. *Fundamental Research in High Energy Density Science*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26728.

Prepublication Copy – Subject to Further Editorial Correction

Fundamental Research in High Energy Density Science

Committee on the Assessment of High Energy Density Science

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

National Academies of Sciences, Engineering, and Medicine

National Academies Press
Washington, DC

Consensus Study Report

PREPUBLICATION COPY—SUBJECT TO FURTHER EDITORIAL CORRECTION

NATIONAL ACADEMIES PRESS 500 Fifth Street, NW Washington, DC 20001

This study is based on work supported by Contract DE-EP0000026/89233121FNA400329 with the National Nuclear Security Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any agency or organization that provided support for the project.

International Standard Book Number-13: 978-0-309-XXXXX-X
International Standard Book Number-10: 0-309-XXXXX-X
Digital Object Identifier: https://doi.org/10.17226/26728

Copies of this publication are available free of charge from

Board on Physics and Astronomy
National Academies of Sciences, Engineering, and Medicine
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This publication is available from the National Academies Press, 500 Fifth Street, NW, Keck 360, Washington, DC 20001; (800) 624-6242 or (202) 334-3313; http://www.nap.edu.

Printed in the United States of America.

Suggested citation: National Academies of Sciences, Engineering, and Medicine. 2023. *Fundamental Research in High Energy Density Science*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26728.

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

Michael R. Anastasio, Retired
Richard K. Appartaim, Florida A&M University
Farhat Beg, University of California, San Diego
Michael Donovan, Tau Systems
David "Dave" A. Hammer, Cornell University
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Jorge J. Rocca, Colorado State University
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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Steven Zinkle, The University of Tennessee, Knoxville, and Don Lamb, The University of Chicago. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Preface

High energy density (HED) science has emerged in recent years as a vibrant field at the confluence of astrophysics, condensed-matter and plasma physics, materials chemistry, high-pressure research, and planetary science. Spectacular breakthroughs in fundamental science and technology, in experimental and theoretical capabilities—and in potential impacts on society—motivate the present review of the field.

Through the National Defense Authorization Act for Fiscal Year 2020, Congress directed the National Nuclear Security Administration (NNSA) to sponsor this study with an emphasis on basic science. Both NNSA and congressional staff reaffirmed this emphasis at the committee's first meeting, which is reflected in the report. However, the committee also celebrates the broader impact of the science on society at large, and on NNSA's capabilities looking toward the future. We also acknowledge the interface between the science and considerations of national and international security, such as the proliferation of powerful, potentially harmful technologies.

As chairs, we benefited from working with a committee of unparalleled excellence and experience in world-class research and scientific leadership, in computational modeling and theory, and fields ranging from high-intensity lasers to high-energy physics. Our work was almost entirely remote, due to the COVID-19 pandemic, with only one in-person meeting between the start of the study in summer 2021 and completion of the report in summer 2022.

The committee converged on the following key themes: modern experimental and computational capabilities are outstanding and there are opportunities for significant advances; diversity in the workplace is crucial, and excellence is nurtured by providing a positive workplace environment for the most important resource of the field—its people; and there are huge opportunities for advances in science and technology, and providing substantial benefits to society. Inevitably, the committee was also confronted with the impact of current events on the science and research community, ranging from domestic matters (e.g., tinyurl.com/mu966zk6) to threats of nuclear war in international affairs.

The committee's views were shaped by important documentation and testimonials from across the research community provided through virtual site visits with key HED laboratories in the United States, Europe and Asia (the latter to address the international assessments in our tasking), and virtual town hall meetings that were accessible to researchers and professional research societies. The vitality of the science was evident from the response we had at all levels, from students and young researchers to senior colleagues, and from technical staff to laboratory directors.

We thank all these colleagues for their helpful comments and for their patience and understanding with us throughout the study. Lastly, we would like to express our appreciation to the staff of the National Academies for their efforts to organize this activity and to keep us on track.

Giulia Galli and Raymond Jeanloz, *Co-Chairs*
Committee on the Assessment of High Energy Density Science

Executive Summary

At the extremes of temperature and pressure found in stars, at the centers of giant planets, and associated with nuclear reactions, materials exhibit properties not observed in our everyday environment—nonmetals become metals, crystals take on surprisingly complex structures, and mass can be converted into energy. These are the conditions of high energy density (HED) science, a rapidly evolving research frontier with societal impact ranging from security to sustainability.

Significant advances in the past decades have increased our ability to create high energy density environments in the laboratory, enabling the discovery of novel behaviors and deepening theoretical knowledge of matter, with essential applications for technology. HED science is now scientifically poised to address several "Grand Challenges," including the following:

- How can nuclear fusion be controlled and harnessed for society's energy, security, and technology needs?
- What are the quantum states of matter in the HED regime that lead to new classes of materials for energy transport, storage, and quantum information science?
- How can we understand matter and processes at extreme HED conditions over a vast range of distance and time scales?
- How can the conditions of extreme astrophysical phenomena evident from observations or predicted by theory be reproduced and studied in the laboratory to increase our understanding of the cosmos?

Congress requested that the National Nuclear Security Administration (NNSA) engage the National Academies of Sciences, Engineering, and Medicine to produce an unclassified, publicly available assessment of recent advances and the current status of research in the field of high energy density physics. Chapter 1 describes the approach of the Committee on the Assessment of High Energy Density Science to address this request to produce a report that assesses fundamental HED science.

Continued progress in HED science depends not only on exceptional facilities, but also on the best minds bringing fresh insight from diverse perspectives to bear on these promising challenges. While HED science has unique characteristics, including those due to its proximity to research bearing on energy and on nuclear weapons, it has been the beneficiary of a world-class system of higher education, a research environment that emphasizes integrity, and a welcoming approach to the world's best researchers.

The new opportunities offered by HED science require urgent attention if the United States is to continue in a leadership role. The competitive economy emerging from the COVID-19 pandemic requires novel approaches to training, recruiting, and retaining scientists, engineers, and technicians, including innovative approaches to university curricula, increased outreach, and improvements to workplace culture.

International collaboration is growing in importance—significant global investments in HED science research facilities have already led to a loss of U.S. pre-eminence in some areas—high-intensity lasers, for example. As the global competition for talent increases in a world of rising international tension, the United States requires a renewed focus on attracting and retaining international talent to maintain a leadership role.

These needs lead the committee to the following key conclusion:

Key Conclusion: An overarching challenge facing the NNSA is retention and recruitment of its expert workforce. The rapidly expanding influence of the private sector, developments around the world, and challenges to workplace climate put at risk the approaches and laboratories in HED science research that have served the nation well since World War II.

Regardless, the committee is optimistic. HED science is making striking advances. Exciting challenges and discoveries attract talented young researchers to the field. Strategic planning for next-generation HED science experimental facilities and computational capabilities are essential for these discoveries, which leverage the breakthroughs being made today. Compelling fundamental science questions, as well as national needs in technology, position HED science as a critical investment with significant promise for society and for our understanding of the universe.

The following recommendations address these observations.

Leading Recommendation: To strengthen its global leadership in high energy density (HED) science and address future national needs, the NNSA should exploit and enhance the capabilities of its flagship HED facilities (e.g., the National Ignition Facility, Z Pulsed Power Facility, and Omega Laser Facility) by establishing plans over the next 5 years for (1) extending, upgrading, or replacing those facilities; (2) increasing the promotion of forefront technology development, including in high-intensity lasers; (3) enhancing academic capabilities and mid-scale facilities; and (4) broadening remote access to its major experimental and computing facilities.

Leading Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should (1) broaden its current programs for achieving excellence through diversity, equity, and inclusion while improving workplace climate and (2) develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, such as for collaborators internationally, and with academia and the private sector.

Additional recommendations from this study are summarized at the end of Chapter 1, and all recommendations appear as a list in Appendix D.

1

High Energy Density Science: Understanding Matter at Extremes

OVERVIEW

High energy density (HED) science seeks to understand and control material at extreme conditions—at temperatures over 20,000°F (approximately 10,000°C, or 10^4 K), pressures millions of times larger than atmospheric pressure,[1] or within electromagnetic or radiation fields that significantly alter the electronic structure of atoms. These conditions can be found deep inside planets and stars throughout the universe, and can also be produced in the laboratory by concentrating energy into small volumes. At these conditions, the forces between atoms, electrons, ions and even nucleons are profoundly modified, changing fundamental material properties, paving paths to the creation of entirely new forms of matter, and enabling conversion of matter into energy.

Traditionally, the domain of HED science is defined by pressures exceeding 1 million times atmospheric pressure (see Figure 1.1). This corresponds to an energy density of 100 billion J/m^3 (Pa), rivaling the quantum forces that determine material structure and properties (see Box 1.1). For perspective, to bring water to the HED regime requires about 100,000 times the energy needed to bring water to its boiling temperature at 1 atmosphere. As such large amounts of energy are hard to come by, MJ or more on laboratory scales (meters), most laboratory HED experiments use small sample volumes of microliters (mm^3) or less.

This introduces a primary challenge in HED science, of controlling experiments and measurements within small volumes, and—for dynamic experiments—on short timescales, corresponding to dynamic times under a millionth of a second. Fortunately, there are multiple approaches to delivering energy in the laboratory: small samples can be compressed between the tips of diamonds; high-intensity optical lasers and high-electric-current, pulsed power can be used to both heat and compress material; and, for example, bright, X-ray free, electron lasers (XFELs) can strip electrons from atomic cores. XFELs represent an exciting frontier for HED science, and while this report focuses on opportunities related to National Nuclear Security Administration (NNSA) facilities, there are many opportunities in the broader Department of Energy (DOE) complex and wider university networks.

When materials are compressed to HED pressures without heating, the distance between atoms shrinks and chemical bonds are significantly modified. The trends of the Periodic Table of chemical elements are thus fundamentally transformed in the HED regime, with new materials, properties, and processes being observed. Hydrogen and helium, the most abundant chemical elements in the universe, transform to fluid metals at high energy density conditions, for example, with liquid metallic hydrogen being the predominant constituent of stars and giant planets (see Figure 1.2).

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[1] A note on units: In the extreme conditions of high energy density (HED) science, familiar units become cumbersome. In the present report, units of temperature are usually reported in degrees kelvin (K) or electronvolts (eV). The Kelvin scale is the same as Celsius (C) but starts at absolute zero temperature such that 0 K = –273°C. At high temperatures, the difference between Celsius and kelvin is often unimportant. An energy of 1 eV corresponds to a temperature of 11,606 K ≈ 10^4 K, so that 1000 eV = 1 keV translates to about 10^7 K; room temperature is about 0.02 eV. Units of pressure are usually reported as multiples of either atmospheric pressure (1 atm = 1.013 bar) or the SI pressure unit Pascal (Pa), with 1 Pa = 1 J/m^3. Earth's average atmospheric pressure at sea level is close to 1 bar or 100,000 Pa = 10^5 Pa; HED science considers materials at pressures above 100 GPa = 100 billion Pa, which is the same as 1 Mbar = 1 million atm.

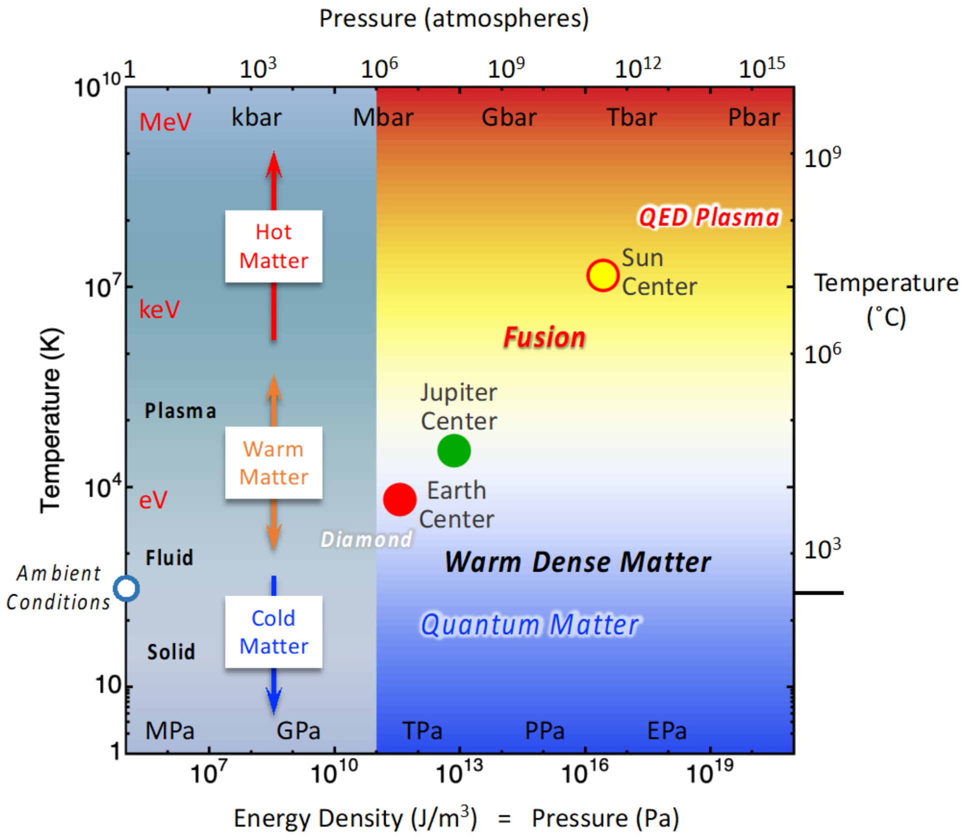

FIGURE 1.1 The regimes of high energy density (HED) science. At Earth-surface pressures and at temperatures of order 100-1000 (10^2-10^3) K, solids melt to form liquids and evaporate to become gases. At higher temperatures, in the 10^3-10^4 K range, electrons can escape individual atoms to form ions. With this ionization process, atoms are no longer electrically neutral, and the resulting mixture of ions and electrons—plasma—is an electrically conducting gas.[2] For condensed matter, this is the beginning of the HED regime at high temperatures and low pressures (or low material densities). Above about 10^7 K, the collisions between atoms (ions) become frequent and violent enough that their nuclei begin to combine and react, leading to nuclear fusion. In HED science, "hot" is shorthand for the many kiloelectronvolts temperature that support nuclear fusion; "warm" indicates the many electronvolts (10^3-10^6 K) temperatures at which thermal effects are significant; and "cold" is limited to matter that is not thermally ionized (below 10^3 K), where quantum behavior often dominates. At any given temperature, increasing material density leads to an increase in pressure that can also affect material on the atomic scale. Cold, electrically insulating materials can transform to metals under compression, and thence to "quantum matter" where collective quantum effects occur. In the regime of dense matter, both quantum and thermal effects exist simultaneously (e.g., pressure ionization and thermal ionization) and interact in complex ways. "Hot dense matter" characterizes the conditions of inertial confinement fusion (ICF), and of the interiors of the Sun and other stars, with densities that can be more than 100 times those of a typical terrestrial solid at ambient conditions. Note that QED is quantum electrodynamic.

[2] Plasma as an ionized, high-temperature gas has nothing to do with blood plasma, and it is an unfortunate quirk of language that the same term is used for completely unrelated materials.

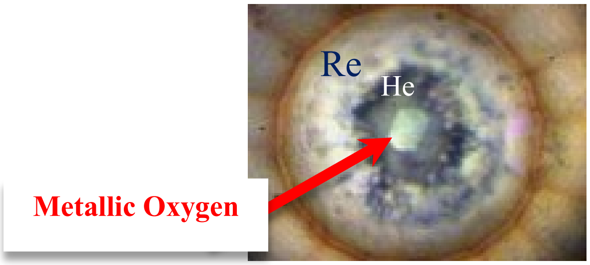

FIGURE 1.2 Many elements and compounds become metals at high pressures. The reflecting sample at the center of the image is a crystal of metallic oxygen at 125 GPa and room temperature inside a diamond-anvil cell. The oxygen (~20 µm in size) is surrounded by helium (gray), contained inside a rhenium foil (outer mottled-reflecting region).
SOURCE: Courtesy of Gunnar Weck, French Alternative Energies and Atomic Energy Commission.

Diamond, a high-pressure form of carbon, is emblematic of how even modest forays toward the HED regime can lead to materials with extreme properties, including strength, transparency, and conduction of heat (see Box 1.2). "Quantum matter" is the cold, high-density regime at which atoms behave "collectively" rather than near-randomly, exhibiting such properties as superconductivity or superfluidity (see Figure 1.3).

When material is heated to high temperatures, for example, by direct irradiation with optical lasers or X rays, or kinetically heated by a high-velocity pressure wave, the electrons that are usually bound to atoms gain enough energy to escape, ionizing the atoms. This leads to the formation of an HED plasma, a high-density gas of charged ions and electrons characterized by strong interactions with external and internal electric, magnetic, and radiation fields. For example, the boundary of the radiation and convection zones of the Sun is highly dependent on material properties in the HED regime, for instance the X-ray opacities of iron and oxygen—that is, how effectively those ionized elements absorb radiation from the stellar core (see Chapter 3).

In the warm dense matter (WDM) regime, a combination of high density and significant temperature lead to complex interactions of quantum and classical phenomena. Here, pressure ionization (due to overlapping of the electron clouds bound to atoms) occurs alongside thermal ionization (atoms losing electrons due to heating), and ions can simultaneously exhibit properties pertinent to both fluids and solids. WDM also makes up much of the planets and stars, and allows for the creation of new materials. While it is experimentally accessible with even low-energy experimental drivers (such as XFELs, and small optical lasers and pulsed power devices), the WDM regime is theoretically and computationally challenging.

Yet more extreme HED conditions can be reached by simultaneously heating and compressing material, as in the spherical implosions of laser inertial confinement fusion (ICF) or the cylindrical implosions of pulsed power magneto-inertial fusion (MIF) (see Appendix A for more detail). These experiments can heat hydrogen to temperatures of tens of millions of degrees kelvin (energies of many kiloelectronvolts) that can support nuclear fusion reactions: collisions of light atoms that convert matter into energy. These are the processes that power the Sun's heat and light and that are now reached in laboratory experiments.

The committee notes that strong magnetic or electric fields and high gravitational forces at planetary or astrophysical scales can also produce HED-relevant conditions, offering promising and relatively new directions of study. However, this report emphasizes recent laboratory experiments and computer simulations and theory, which tend to concentrate on high densities and temperatures.

BOX 1.1
Technical Characteristics of the High Energy Density Limit

The pressure-volume (P–V) work associated with onset of the high energy density (HED) regime, $-P\Delta V$ for $P = 100$ GPa $= 10^{11}$ J/m^3, is of order 1 eV (96.5 kJ/mole), the energy of chemical bonds and of the atom's outermost electrons; constant-volume (isochoric) heating yields similar magnitudes of pressure and energy changes for condensed matter (see Figure 1.1.1).

Characteristic values for the dimension of an atom (1 ångström = 1 Å = 10^{-10} m) and for chemical-bond energies give an energy density of 1 eV/Å^3 = 160 GPa, near the lower limit of HED conditions. Multiplying the HED onset (10^{11} J/m^3) by typical values of atomic volume (Å^3 = 10^{-30} m^3) and atom-dynamics times (1 fs = 10^{-15} s) gives the quantum of action, the reduced Planck's constant: 100 GPa Å^3 fs = 1×10^{-34} J s = $h/2\pi = \hbar$. In short, ångströms and femtoseconds are length and time scales for atoms and molecules combining or reacting, such that 100 GPa corresponds to the quantum of chemistry.

The TPa = 1000 GPa pressures now accessible in a variety of laboratory experiments (see Chapter 2) are comparable to the quantum mechanical forces determining the structure of the atom: $\hbar^2/(4\pi m_e a_0^5)$ = 2.3 TPa is the quantum pressure that keeps the electron from spiraling into the nucleus of the Bohr atom, and $\hbar^2/(m_e a_0^5) = 29$ TPa is the atomic unit of pressure at which not only chemical properties but the structure itself of the atom is profoundly altered (m_e and a_0 are the mass of the electron (9.109×10^{-31} kg) and the Bohr radius (53 pm), respectively). At the kiloelectronvolt energies reached under 10-100 TPa pressures (0.1-1 Gbar), core electrons participate in chemical bonding: these are the conditions of kilovolt chemistry.

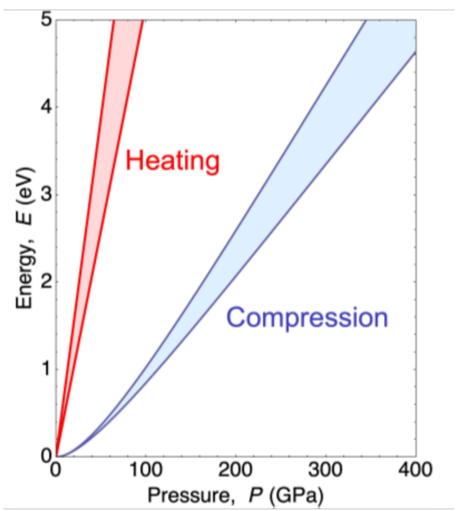

FIGURE 1.1.1 Energy change on compression (*blue*) or constant-volume heating (*red*) to the 100 GPa = 10^{11} J/m^3 pressure range is comparable to chemical-bonding energies (eV), with 1 eV ≈ 10^4 K.
SOURCE: Courtesy of R. Jeanloz.

BOX 1.2
High Energy Density Material: Diamond

Its strength, stiffness, transparency to light over a wide range of wavelengths (from infrared to X ray), and high thermal conductivity make diamond an important technological material, with applications ranging from micro-cutting blades in the clinic to windows for detectors in space, and from quantum sensors in the laboratory to heat sinks for computer chips (see Figure 1.2.1). In nature, diamond is formed inside planets and during planetary impacts, at pressure-temperature conditions close to the high energy density (HED) limit (10^{10} J/m^3). That is, the conditions for diamond to be stable are mainly in the HED regime. However, ingenious methods of chemical vapor deposition (CVD) allow its synthesis at near-ambient conditions in the laboratory, thereby making it possible to manufacture high-quality diamond in large

quantities. The global market for synthetic diamonds is estimated to be about $18 billion per year.

Early HED research guided the way to a widely available class of diamond products, from nanocrystals to gems. HED experiments use gem-quality diamonds to compress materials into the 0.1-1 TPa pressure range, and capsules of nanocrystalline diamond containing solidified hydrogen isotopes (deuterium and tritium or “DT” ice) are used as targets for inertial confinement fusion (ICF) experiments.

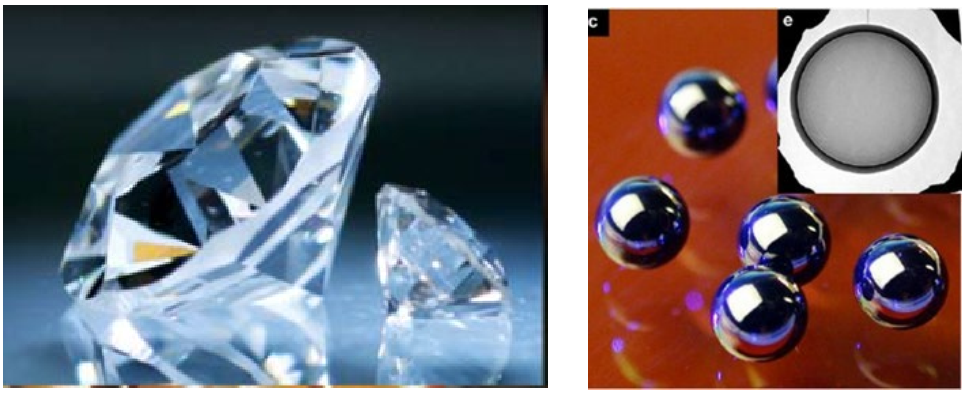

FIGURE 1.2.1 Diamond as used in high energy density science. *Left*: Large (up to 1 cm diameter, 2.4 carat) synthetic diamond anvils used for high-pressure research. *Right*: 2.6 mm-diameter nanocrystalline diamond inertial confinement fusion capsules. *Inset*: X-ray image of a capsule (75 µm wall thickness) that can hold a deuterium and tritium ice layer at 18 K for inertial confinement fusion experiments
SOURCE: *Left*: T. Irifune and R.J. Hemley, 2012, “Synthetic Diamond Opens Windows into the Deep Earth,” *EOS* 93(7):65-66. Copyright 2012 by the American Geophysical Union. *Right*: J. Biener, D.D. Ho, C. Wild, et al., 2009, “Letter: Diamond Spheres for Inertial Confinement Fusion,” *Nuclear Fusion* 49(11):112001.

While the atomic-scale properties of materials at extreme conditions are fundamental to HED science, the behavior and performance of HED *systems* is often most relevant to applications. All HED experiments and astrophysical objects access an enormous range of materials, conditions, length scales, and time scales over the course of their evolution. Thus, it is not sufficient to understand the microphysics of HED science: we must also understand how samples interact with external fields; how inhomogeneous radiation distributions influence plasma evolution; and how instabilities form, grow, and evolve into turbulence and mix.

This variety of phenomena—from the quantum mechanics of chemical bonding, to collective plasma effects, to strong coupling of matter with radiation, to thermonuclear processes, along with the enormous ranges of relevant length and time scales, from the atomic to the astrophysical—leads to some of the fundamental excitement of HED science. And learning how to manipulate and diagnose HED matter can unlock entirely new states of matter, enable the efficient production of exotic materials, generate fusion energy, and reveal the conditions by which planets form and evolve over time.

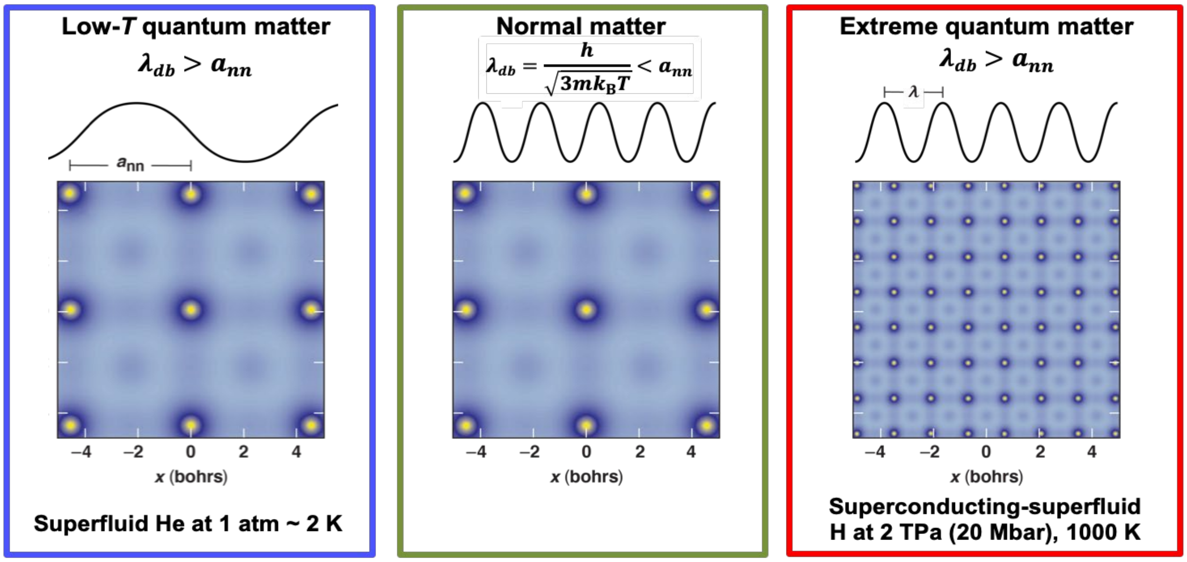

FIGURE 1.3 Important quantum properties of matter such as free-flowing electric currents and liquids appear at high energy density (HED) conditions. Quantum matter at low temperatures (low–T: *left*) or at high pressure (high compression: *right*) is characterized by the separation between nearest-neighbor atoms (a_{nn}) being less than the quantum wavelengths of the atoms themselves (de Broglie wavelength, λ_{db}), $\lambda_{db} > a_{nn}$; whereas normal matter (*center*) is characterized by the de Broglie matter waves having shorter crest-separation than the distances between atoms, $\lambda_{db} < a_{nn}$. (Here, 1 bohr = 0.529 Angstroms.) Quantum effects include "collective" behavior of atoms (superfluidity: fluid flow without any viscous resistance; Bose-Einstein condensation: not labelled) or electrons (superconductivity: electric flow with zero resistivity). Atoms themselves may become quantum-indistinguishable as their separation becomes smaller than the de Broglie wavelength, here given as $\lambda_{db} = h/\sqrt{(3mk_BT)}$, where h is Planck's constant, m is the mass of the atom, k_B is Boltzmann's constant, and T is temperature in kelvin. Low-temperature atomic, molecular, and optical physics traditionally focuses on low-temperature conditions (*left*), and HED science is now characterizing the complementary HED regime (*right*).
SOURCE: Courtesy of G. Collins.

Today, HED science spans many topics and disciplines, from astrophysics and chemistry, to materials science and physics (see Boxes 1.3 and 1.4). Computational science brings the tools of atomistic simulations and artificial intelligence, as well as well as fluid dynamics, optics, and condensed-matter and plasma theory (e.g., laser-plasma interactions). And HED research engages academic, national laboratory, and industry partners worldwide at the frontier of scientific discovery and its societal applications.

Progress in fundamental HED research at national laboratories and universities, and through international collaboration, has been critical in refining our understanding of these applications, with investments in this domain already yielding important returns. Continued investment will therefore be important for technology applications as well as the broader field of HED science.

In anticipation of continued advances in both computational and experimental capabilities, the committee prepared this report to assess the accomplishments, opportunities, and challenges of basic research in HED science.

In addition, HED science has applications in core mission areas of the NNSA, including stewardship of the nation's nuclear weapons stockpile, countering proliferation of the associated technologies, and development of nuclear fusion–based energy capabilities: areas in which the basic research described in the text by the committee is essential to (1) advancing the underlying science and (2) assuring that the workforce continues to maintain its high level of expertise in the future. A complementary, congressionally mandated study on HED research for stockpile stewardship was separately prepared in

response to a request in the 2019 NDAA. The present study is entirely about open science, engineering, and technology and did not consider classified topics or materials.

BOX 1.3
The Language of High Energy Density Science

Atomic pressures. Pressures at or above the atomic unit of pressure, roughly 30 TPa (see Box 1.1), at which the external forces begin to overwhelm the intrinsic forces of atoms, changing the nature of atoms themselves.

Cold matter. Matter that is not ionized by temperature, typically solids or fluids at temperatures below 10^2-10^3 K (= 0.01-0.1 eV energies), and often implying quantum properties.

Condensed matter. Solids and fluids comprising much of the matter that we interact with on a daily basis and characterized by significantly higher densities than gases. At ambient or Earth-surface conditions (10^5 Pa, 300 K), condensed matter has densities of about 1-20 g/cm^3, depending on chemical composition (the density of water is 1 g/cm^3, for example), whereas gases have densities of about 10^{-3}-10^{-1} g/cm^3.

Degenerate matter. Matter for which the density is high enough and the temperature low enough that quantum statistics are required to determine material properties.

Dense matter. Matter under pressure, hence compressed to higher densities than at ambient (Earth-surface) conditions, for instance to densities 10-, 100- or even 1,000-fold higher than ambient.

Dense plasma. Dense fluid at high enough temperatures to be ionized, hence electrically conducting. ***Coulomb jelly*** *(or jellium)* and ***Coulomb fluid*** are sometimes used to convey the same meaning.

High energy density matter. Matter at pressures above 10^{11} Joules/m^3 = 100 GPa, conditions for which external forces begin to overwhelm chemical forces of ordinary matter on Earth.

Hot matter. Matter at high enough temperatures to sustain nuclear fusion (typically above 10^7 K ~ 1 keV).

Nuclear fusion. The process of atomic nuclei combining with a release of energy and particles (e.g., neutrons), typically at temperatures above 10^7 K = 1 keV. Nuclear burning refers to enough energy and particles (especially helium nuclei) being released by the nuclear reactions to trigger nuclear fusion in surrounding material. Nuclear ignition refers to more energy being released by the nuclear reactions than was required to create the conditions for nuclear fusion.

Nuclear matter. Matter at pressures so great as to engage the strong and weak nuclear forces, overwhelming the Coulomb repulsion of ions.

Plasma. Matter at high enough temperatures to be an ionized gas (typically at or above 10^3-10^6 K = 10^{-1}-10^2 eV): electrons released (ionized) from the atoms cause the gas to be electrically conducting.

Quantum matter. Matter exhibiting quantum behavior, often characterized by the atom or electron wavelengths (de Broglie wavelengths) exceeding the separation between atoms. This can occur at very low temperatures or very high densities, or both low temperatures and high densities (see Figure 1.3).

Radiative plasma. Ionized matter for which the radiation pressure is comparable to or greater than the thermal pressure.

Relativistic plasma. Ionized matter for which the electron velocities (thermal velocity at high temperature, or Fermi velocity at high density) are a significant fraction of (e.g., more than ~1/10) the speed of light.

Warm matter. Matter typically at "classical" conditions, neither quantum nor thermonuclear, roughly at temperatures of 10^2-10^6 K ≈ 1-100 eV energies. ***Warm dense matter*** is the regime of this matter above ~100 GPa at which several energy scales are comparable, including the Coulomb, thermal, Fermi, and plasmon energies. Traditional approximations used in plasma or condensed-matter physics may not be reliable in this regime.

Weakly coupled plasma. Plasma for which the electrostatic (Coulomb) energies of the ionized gas are less than the thermal and/or quantum statistical (Fermi) energies. ***Strongly coupled plasma*** indicates the opposite condition of electrostatic energies exceeding thermal and Fermi energies.

BOX 1.4
Scientific Disciplines of High Energy Density Science

High energy density science lies at the intersection of many research domains, combining the concepts and terminology of the following and other scientific disciplines.

- Astrophysics
- Atomic and molecular physics
- Chemical physics
- Computational chemistry, physics, and materials science
- Condensed-matter chemistry and physics
- Electromagnetism
- Fluid dynamics
- High-pressure research
- Laser science
- Low-temperature physics
- Magnetohydrodynamics
- Materials chemistry and physics
- Mineral physics
- Nuclear physics
- Opticsplanetary geophysics
- Plasma physics
- Pulsed power
- Quantum mechanics
- Radiation hydrodynamics
- Statistical/thermal mechanics

STATEMENT OF TASK AND IMPLEMENTATION

This study is in response to Section 3137 of the 2020 National Defense Authorization Act (NDAA; Public Law 116-92) requesting that the NNSA engage the National Academies to produce an unclassified, publicly available assessment of recent advances and the current status of research in the field of high energy density physics. The statement of task as determined by the NNSA and the National Academies follows.

Statement of Task

The National Academies shall establish a committee that will articulate the recent advances, status, and future directions of high energy density (HED) physics in the United States. The committee will consider HED physics as the physics of matter and radiation at energy densities exceeding 1×10^{11} J/m^3 or other temperature and pressure ranges within the warm dense matter regime. It will include a particular focus on HED material phases, plasmas atypical of astrophysical conditions, and conditions of interest to the National Nuclear Security Administration (NNSA). The committee will then develop a report that will:

- Assess the progress and achievements in HED physics over the last decade, including theory, computation, modeling and simulation, driver development, instrument development, emerging technologies, analytical methods, and target fabrication.
- Identify major scientific gaps and potential new directions in areas of modeling, simulation, instrumentation, and target fabrication that offer the most promising near- and mid-term investment opportunities.
- Identify challenges that the field may face over the next decade in realizing those opportunities and offer guidance for addressing them, including, but not limited to, investment level, interagency collaboration, research tools, and infrastructure.
- Evaluate the role of HED physics in developing an expert workforce for NNSA and assess whether changes in resources, scientific focus, access to experimental facilities, or funding levels are necessary to meet nuclear security workforce needs in the coming decade.
- Assess the state and recent advances made by other countries in HED physics and discuss the relative standing of the United States.

Implementation

To ensure that it would address the issues of the sponsor's interest, the committee's first meeting included a discussion with staff from Congress and NNSA regarding the statement of task. (Appendix E summarizes the committee's activities). These groups, which the committee treated as sponsors, reaffirmed their original intent for an unclassified study resulting in a publicly available report that assesses fundamental HED science, complementing a classified study of programmatic efforts in HED science that had been previously completed for NNSA (as requested in the 2019 NDAA).

Therefore, the committee studied the topics described in the statement of task, including "HED material phases, plasmas atypical of astrophysical conditions, and conditions of interest to the National Nuclear Security Administration," in the broader context of the fundamental science, rather than limiting itself to NNSA's current programs. This context is reflected in the committee's analysis of HED science as a whole, including areas of physics, chemistry, materials science, planetary science, astrophysics, plasma physics, and various technological applications. These are but representative examples of research directions that are currently having a high impact.

Similarly, in response to gaps recognized in the current programs, capabilities or research domains, the committee did its best to identify the most promising directions for future research that can fill those gaps and provide new scientific perspectives. This focus on actionable opportunities is needed to advance the science as rapidly and effectively as possible.

REPORT CONCLUSIONS AND RECOMMENDATIONS

The committee organized this report to contain leading and major recommendations, as well as more general recommendations, conclusions, and findings.

Leading recommendations, such as those in the Executive Summary (and immediately below), present the committee's main, overarching vision for the future. Major recommendations, listed in the

following subsection, represent key initiatives for advancing HED science and are further elaborated in the following chapters. The remaining recommendations are important for growth of the field in terms of collaborations, capacity, and culture that can sustain the NNSA mission and serve the nation into the future. Findings (typically, findings of fact) and conclusions (inferences based on information the committee has gathered) are also noted.

Key Report Conclusion and Leading Recommendations

Key Conclusion: An overarching challenge facing the NNSA is retention and recruitment of its expert workforce. The rapidly expanding influence of the private sector, developments around the world, and challenges to workplace climate put at risk the approach and laboratories in HED science research that have served the nation well since World War II.

> **Leading Recommendation: To strengthen its global leadership in high energy density (HED) science and address future national needs, the NNSA should exploit and enhance the capabilities of its flagship HED facilities (e.g., the National Ignition Facility, Z Pulsed Power Facility, and Omega Laser Facility) by establishing plans over the next 5 years for (1) extending, upgrading, or replacing those facilities; (2) increasing the promotion of forefront technology development, including in high-intensity lasers; (3) enhancing academic capabilities and mid-scale facilities; and (4) broadening remote access to its major experimental and computing facilities.**
>
> **Leading Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should (1) broaden its current programs for achieving excellence through diversity, equity, and inclusion while improving workplace climate and (2) develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, such as for collaborators internationally, and with academia and the private sector.**

Major Report Recommendations

Major Recommendation: The NNSA should work with the academic and national laboratory user community, relevant government agencies, and industry to develop a high-performance computing (HPC) strategy for high energy density science over the next 2 years. This strategy should include benchmarking and the verification and validation of codes, code comparisons, the close integration of simulations using HPC with experiments, co-development of hardware and software for the research community, open-source documentation of codes and experimental results in a standardized open format (e.g., to enhance use and effectiveness of machine learning and artificial intelligence tools), and an industry-relevant implementation plan.

Major Recommendation: The NNSA and the national laboratories should, in coordination with partner science agencies (e.g., including the Department of Energy's Office of Science and the National Science Foundation), academia, and industry, set expectations for rigorous benchmark experiments that can provide solid foundations for multi-scale high energy density simulations. Particular emphasis should be given to characterizing material properties under extreme and non-equilibrium conditions, including conditions accessible at university- and mid-scale facilities, and develop a new generation of diagnostics that can take advantage of modern technology such as higher repetition rate (e.g., compact light sources) that access a range of time and length scales.

Major Recommendation: The inertial confinement fusion community should redouble efforts to focus on the underlying basic science to (1) achieve robust ignition and the maximum yield with optimal efficiency, (2) establish the best uses of laboratory burning plasmas, and (3) help identify the best path for future experimental and computational facilities. In particular, the sustainment of innovation and breakthrough research will require a careful balance between yield-producing and non-ignition experiments. Additionally, the NNSA should work with the relevant agencies (e.g., the Department of Energy's Fusion Energy Sciences and Advanced Research Projects Agency–Energy and the National Science Foundation) and private industry to leverage research in inertial fusion energy and—where possible—partner in research areas of mutual interest.

READER'S GUIDE AND NOTE ON APPENDIXES

The report is organized into five chapters and several appendixes. Mirroring the study's statement of task, Chapter 2 summarizes recent progress in the field; Chapter 3 points to opportunities to pursue, which also reflect current gaps; Chapter 4 considers the HED science workforce; and Chapter 5 addresses the international HED science landscape.

In seeking a balance with material of interest to a general audience, the committee placed into the appendixes those matters judged to be more relevant to specialists in the field. The committee considers the appendixes as integral to the report.

2

Recent Progress and Opportunities

This chapter describes a selection of recent discoveries in high energy density (HED) science, highlighting advances in basic science and opportunities for contributing to society (see Table 2.1). The intent is to give a sense of the vibrancy of the field. The committee did not attempt to be comprehensive, and many additional important contributions are described in the research literature.

The topics are broadly grouped into the following four categories: (1) physics and materials, (2) origin and evolution of planets and stars, (3) chemistry, and (4) technology with societal impact. However, there is considerable overlap among the examples given, as well as the associated methods and applications. For example, a contribution in materials chemistry may depend on a breakthrough in the underlying physics and have implications for understanding the origins or evolution of the Solar System. Results from both theory and experiment are intertwined, with only the briefest mention of the techniques employed (see Appendixes B and C).

> Finding: HED science has produced spectacular advances in basic science (see, e.g., Table 2.1 and Box 2.3), with potential applications ranging from providing energy (nuclear fusion) to transmitting it efficiently (superconductivity).

PHYSICS AND MATERIALS: MATTER MANIPULATION ON THE QUANTUM SCALE

Pressure Metallization and Un-metallization

One of the most dramatic effects of pressure is the transformation of many chemical elements and compounds into the metallic state, characterized by high electrical conductivity, as well as high opacity to and reflectivity of visible light. For example, hydrogen, helium, and oxygen—transparent, electrically insulating gases at ambient conditions—all transform to fluid, opaque (and reflective), electrical conductors at HED conditions of high temperatures and pressures.

Hydrogen is of special interest because it is the most abundant chemical element of the universe, and fluid metallic hydrogen is the primary constituent of stars and giant planets. The smallest atom of the Periodic Table, hydrogen has particular significance for theory as well as experiments, with the search for crystalline metallic hydrogen attracting considerable interest for the past 85 years (see Box 2.1).

Experiments using several distinct techniques, from gas-gun impacts and dynamically heated diamond cells to laser- and magnetic-driven compression, confirm that fluid hydrogen starts metallizing below 100 GPa at temperatures of about 3000 K. Both experiments and theory indicated that the metallization pressure increases with decreasing temperature, and crystalline hydrogen has yet to be definitively metallized at room temperature, with recent room-temperature experiments now extending up to 500 GPa.

BOX 2.1
Hydrogen: The "Holy Grail" of High Energy Density Science

Hydrogen, although the simplest element, with only a single electron per atom, forms a complex condensed-matter system. It is worthy of study because it is the most abundant element in the universe. The Sun and other stars, along with giant planets such as Jupiter and Saturn, are primarily made of hydrogen. Most of this hydrogen is under extreme conditions of pressure and temperature, so detailed understanding of the properties of hot, dense hydrogen is essential to understanding the origin and structure of these and many extrasolar planets. Hydrogen, under everyday conditions, is ubiquitous and of vital importance to future technological developments. The committee mentions the "hydrogen fuel economy," hydrogen's importance for fusion, and its record-setting superconducting properties.

As pure hydrogen is pressurized, it is thought to transform from a molecular solid into a metallic atomic superconductor at low temperatures. This quantum state of hydrogen, hypothesized for many years, has not been definitively observed yet, although tantalizing evidence has been obtained in a few experiments. What has been found are several distinct crystalline and liquid phases of hydrogen, with more expected as the temperature and pressure ranges are extended. Although challenging, hydrogen serves as an important reference point for theory, computer simulation, modeling, and experimentation. The goal is to achieve precise agreement between the various approaches and models.

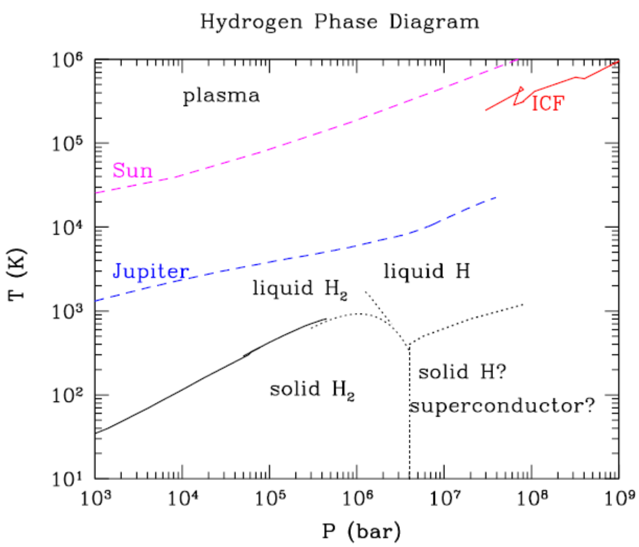

FIGURE 2.1.1 Phase diagram for elemental hydrogen. The horizontal axis shows the pressure in bars (1 bar = 105 Pa); the vertical axis the temperature in kelvin (room temperature is near 300 K). Solid (crystalline) hydrogen is found at low temperatures. The transition from molecular hydrogen (H_2) to atomic hydrogen (H) is believed to occur at about 5 million bars (500 GPa), with solid atomic H thought to be a superconductor even at room temperature. Solid lines show transitions established in the laboratory; dotted lines those predicted by theory. The dashed lines labeled Jupiter and Sun show the conditions of temperature and pressure within those bodies; ICF (inertial confinement fusion) indicates the conditions of a capsule undergoing laser compression.
SOURCE: Courtesy of D. Ceperley.

This last result is at odds with decades' worth of theoretical expectation, which predicted that crystalline hydrogen should metallize more easily—not less easily—than fluid hydrogen. The discrepancy between theory and experiment appears now to be largely resolved, with modern theory in line with experimental results (see Table 2.1). However, the case of hydrogen illustrates both the challenge of theoretically predicting material properties, even for the simplest atom of the Periodic Table, and the necessity of leveraging theory and experiment together.

More generally, there is a close relationship between phenomena labeled as the metal-insulator transition of cold or warm-dense matter, continuum lowering in hot-dense plasmas, and electron localization of electrides in chemistry. The differences between these concepts and terminology have made it difficult to understand the relationships between these processes, and the transition between electrically insulating and conducting matter continues to be a rich topic for research in the high energy density realm.

Helium is important as the second-most abundant element of the universe, stars, and giant planets, and it is no-doubt the most challenging atom to metallize (its high ionization energy is a quantum effect). Still, fluid metallic helium has been produced and characterized in the laboratory, with theory revealing how its metallization differs from the high-temperature ionization associated with low-density helium plasmas. As discussed below, the more extreme pressure–temperature (P–T) conditions needed to metallize helium relative to hydrogen has important implications for planetary chemistry.

Diamond and even oxides (among the most common ceramic materials) are likewise found to transform to metals at terapascal pressures. The metallization of carbon, theoretically predicted and supported by experimental results, may limit diamond-anvil cells to maximum pressures of about 1 TPa.

The reason that pressure tends to metallize elements and compounds is that as atoms are squeezed together, their electrons tend to avoid each other, both because the negatively charged electrons repel one another and for quantum mechanical reasons (see Figure 2.1). The atomic orbitals are thereby smeared out, such that the atoms' outer electrons can move from one ion to the next (electrons become "delocalized"). The material becomes electrically conducting, and—as described below—can even become superconducting.

Theory predicted that this simple explanation of metallization can be reversed, however, in that pressure can also cause some metals to become nonmetallic. The idea is that compression shapes the spatial distribution of electrons, such that electron clouds are piled up between the ions (see Figure 2.2). This change in electron distribution amounts to creating an ionic bond.

The theoretical prediction of pressure-induced electron "localization" was dramatically confirmed with the observation that sodium—normally considered among the simplest of metals at ambient conditions—becomes transparent and electrically insulating by 200 GPa pressure (see Figure 2.3). Effectively, Na transforms to Na-e^- (electride), analogous to the salt NaCl but with the "anion" being an electron cloud (e^-) rather than an ion (Cl^-). Theory predicts that other elements, such as aluminum, can exhibit similar transitions from metal to insulator and then transform back to metals again at yet higher compressions. In fact, such behavior might be ubiquitous for elements and compounds at sufficiently high pressures, opening a new chapter in HED matter research, with pressure being used to create and mold new chemical bonds, as guided by theory.

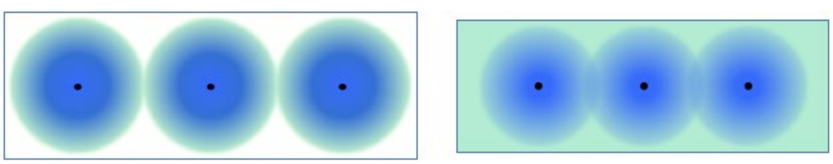

FIGURE 2.1 As atoms are brought together, their outer electron clouds touch (*left*) and join to form a metallic state (*right*). Each atom consists of a positively charged nucleus (*dark blue point*) surrounded by negatively charged electron orbitals (*blue* and *green*). At high enough compression, the outer orbitals are smeared into a sea of moving, "delocalized" electrons (*green* at *right*) that can carry electrical currents between the ions (*blue*).
SOURCE: Courtesy of R. Jeanloz.

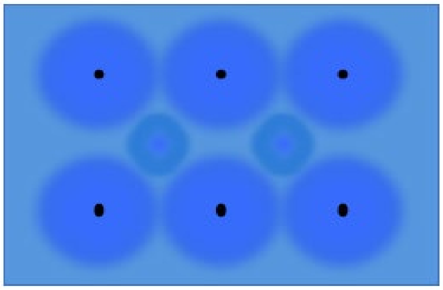

FIGURE 2.2 Compression causes electrons to pile up between ions (atoms with nuclei), thereby pinning down the electrons and transforming the metal to a non-metallic state. Each atom consists of a positively charged nucleus (*dark blue point*) surrounded by negatively charged electron orbitals (*blue*). At high enough compression, electrons become localized and concentrated between the ions (two clouds without nuclei, shown in *blue* near *center*), transforming the metal to an insulating electride (analogous to a salt).
SOURCE: Courtesy of R. Jeanloz.

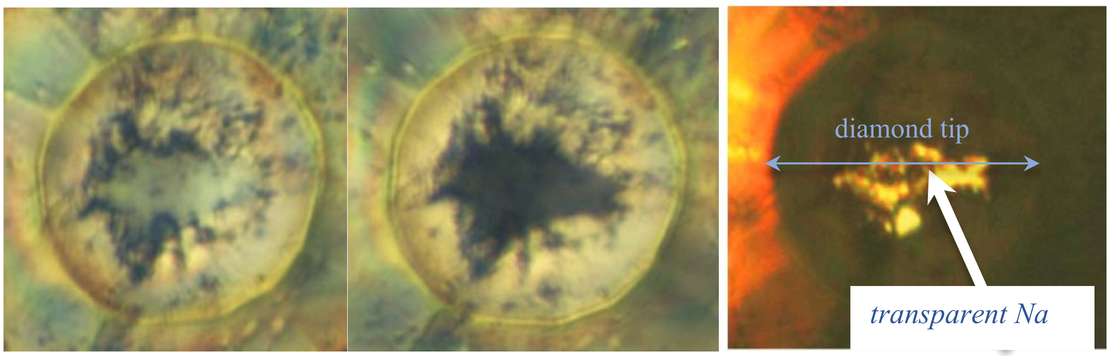

FIGURE 2.3 Visible light can be seen passing through transparent sodium (Na) at 199 GPa (*at right*). Sodium is normally a metal opaque to visible light at ambient conditions and at lower pressures—for example, at 125 GPa (reflective of visible light) and 156 GPa (no longer reflecting light), respectively, in the images at *left* and *center*. The sample is observed through a diamond-anvil cell at room temperature, with the diamond tip being about 40 μm across. In the right image, light reflecting off some of the diamond facets is seen on the left side of the image.
SOURCE: Reprinted by permission from Springer Nature: Y. Ma, M. Eremets, A. Oganov, et al., 2009, “Transparent Dense Sodium,” *Nature* 458:182-185; © 2009.

Gigabar Compression and Ionization of Electron Shells

It was a major technical breakthrough nearly 50 years ago, when development of diamond-anvil cells made it possible to study materials at static pressures of 100 GPa in the laboratory. Dynamic-compression experiments were already probing the 0.1-0.5 TPa (100-500 GPa) range over time periods up to 1 μs, but now it was possible to create new materials and characterize them for arbitrarily long periods of time at the megabar (million-atmosphere) pressures that alter chemical-bonding energies; that is, at the onset of the HED regime.

Static experiments now reach 1 TPa (1000 GPa), and the most accurate dynamic experiments use magnetic- or laser-driven planar compression to achieve 2-10 TPa, respectively. These experiments provide some of the first experimental checks of “statistical atom” theory that is widely used to understand the interiors of stars and giant planets, confirming as well as extending these atomic models (e.g., Thomas-Fermi-Dirac theory).

It is therefore a spectacular accomplishment that experiments have recently been extended to the 10-100 TPa (gigabar, or billion-atmosphere) realm by way of spherically convergent laser-driven experiments. This means that laboratory measurements are now being made at atomic-scale pressures (29 TPa), conditions overwhelming the quantum forces that determine atomic structure at ambient conditions (see Box 2.2). The combined *P–T* ionization of atoms' different electron-orbital shells can thus be quantified and directly compared with long-standing theoretical predictions (see Figure 2.4).

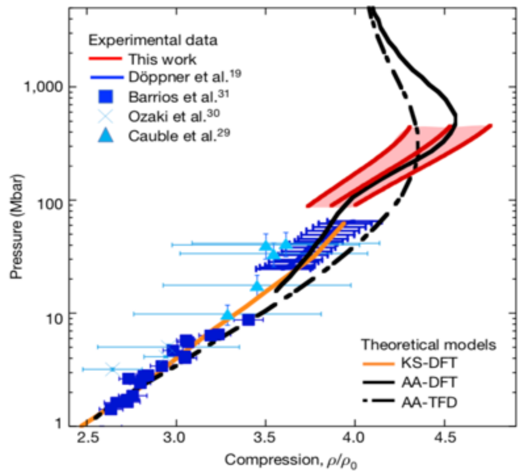

FIGURE 2.4 Equation of state measurements toward 100 TPa (1 Gbar = 1000 Mbar) conditions (*red*) show good agreement with modern theory for pressure-ionized matter (DFT or "Density Functional Theory": *solid black curve*). Spherically convergent experiments on polystyrene significantly extend prior laboratory measurements (*blue*) and can discriminate between more modern theory (DFT curve) versus older theory (TFD or "Thomas Fermi Dirac": *dash-dot black curve*) describing the effects of ionization, reflected here in the compression curve oscillating and turning back on itself at pressures above 10 TPa. AA and KS represent different methods—that is, "average atom" and "Kohn-Sham," respectively.
SOURCE: Reprinted by permission from Springer Nature: A.L. Kritcher, D.C. Swift, T. Döppner, et al., "A Measurement of the Equation of State of Carbon Envelopes of White Dwarfs," *Nature* 584:51-54; © 2020.

Finding: Many experimental methods can now access the HED regime exceeding 0.1 TPa (1 million atmospheres pressure) at which chemical bonding is changed, from static compression using diamond-anvil cells to mechanical impact and laser- and magnetic-driven dynamic compression.

Finding: High-quality measurements are possible well into the HED regime, to 0.5-1 TPa statically, and to 1-10 TPa through shock or ramp loading; pioneering laboratory measurements are exploring the 10-100 TPa (0.1-1 billion atmosphere) range of pressures at which atomic structure is altered and new types of chemical bonding emerge.

ORIGIN AND EVOLUTION OF THE SOLAR SYSTEM

Iron Opacity and the Sun's Composition

The properties of ions are important for many applications, from chemistry to astrophysics. A notable example is the absorption of light by such atoms that have lost some or all of their electrons, whether as a high-temperature plasma or as pressure-ionized matter (e.g., Figures 2.1 and 2.4). Although important,

this ion opacity is difficult to calculate theoretically, and historically even more difficult to measure at HED conditions. The difficulty of calculations, which require not only extensive atomic structure but also dense-plasma effects, is compounded by the relatively few atomic physicists who focus on HED conditions.

The recent experimental measurement of iron opacity was therefore widely considered a major contribution, not only as a technical accomplishment—the fact that the opacity of ionized iron could be successfully measured—but also because it helps address a problem in understanding the Sun's composition. (See Table 2.1.) Spectroscopic determinations of the solar iron abundance appeared to be in conflict with theoretical analysis of the Sun's observed oscillations, unless previous estimates of opacity were too low. As it happens, the new laboratory measurements revise past estimates upward, but await confirmation—more measurements are surely warranted to follow up on this pioneering work—and underscore the importance of maintaining and even developing a variety of independent capabilities for both theory and experiments. Still, the new opacity measurement has had considerable impact across the scientific disciplines because there is a close linkage between the composition of a star and its planets, so the result can play a key role in advancing current understanding of planetary origins and evolution as applied to thousands of extra-solar planets.

Planet Formation and Evolution

The origins and evolution of Jupiter and Saturn are also of special interest because these planets are thought to have formed early in Solar System history, potentially offering Earth protection from giant, planet-destroying impacts as the planet formed and grew.

One of the major open questions about the large planets concerns the rates at which Jupiter and Saturn lose heat and evolve over their multi-billion-year histories. These planets consist mainly of hydrogen and helium. Theories developed over the decades show that the cooling rates are influenced by the heavier element helium "raining" downward through the lighter hydrogen, thereby releasing gravitational energy that heats the deep interior as the planet rearranges itself with heavier elements concentrating toward the center.

Astrophysicists cannot do experiments in space. On the other hand, HED experiments can be carried out under the same temperature and pressure conditions present in the cores of these large planets. In particular, experiments over the past 5 years show that there is a range of pressures (hence depths) within Jupiter and Saturn at which hydrogen is metallic but helium is not; due to the difference in chemical bonding, the two fluids do not mix but instead separate, like oil and water. The recent experiments provide laboratory evidence for the proposed unmixing and raining out of helium within the giant planets, confirming that this process plays an important role in the long-term evolution of the giant planets and explaining why Saturn puts out more heat than it gets from the Sun.

Another type of material chemistry is illustrated by the formation and characterization of a "superionic" form of H_2O ice at high pressures in the laboratory. First predicted by theory, this form of ice has the protons (H^+ ions) moving readily between rigidly packed oxygen ions. Ion conductivity is central to electrochemistry and the technology of modern batteries, and it is significant that such phenomena have now been experimentally documented at high compressions. Indeed, it appears that the superionic form of water ice is a major constituent of such planets as Neptune and Uranus.

High-pressure experiments have prompted theoretical efforts to systematically characterize materials in support of modeling the formation, evolution, and current constitution of planets in our Solar System and beyond. The new First Principles Equation of State (FPEOS) compendium is a case in point of a new contribution from theory fostering powerful new collaborations between astronomers and the HED science community. (See Table 2.1.)

Another perspective on HED science addresses the role of impacts during the gravitational accumulation of mass as a planet forms. Typical orbital velocities around the Sun show that impacts associated planet formation generate terapascal-scale pressures; that is, create HED conditions at the planet's growing surface.

In short, planet formation is a violent process, with comparable-size bodies impacting each other as the planet grows. For example, it is thought that the Moon was splashed out of Earth by a large (roughly Mars-sized) body impacting the planet after it had largely formed, thereby melting much of the planet and all of the material from which the Moon was formed. The properties of the dense rock-metal plasma from which the Earth-Moon system then emerged can only be determined by HED theory and experiments.

Indeed, the Moon's huge impact basins provide a record of major impacts during and shortly after the Earth-Moon system was formed (Earth's ongoing geological activity has mostly wiped out evidence of early large impacts on the planet). The Moon's craters and impact basins provide a record of the tail end of planet formation, and it is evident that Earth was subjected to large enough impacts for 0.5 billion years or more after its formation that early-formed oceans of water would have been boiled away, perhaps many times over.

Such "impact sterilization" seems likely for the early history of Earth and other planets that have the potential to harbor life. Evidence from geochemistry and other domains indicate that life may have already been forming on early Earth, leading to the hypothesis of impact "frustration" of life—that impact-induced HED conditions wipe out emerging life during planet formation. If so, the suggestion is that life emerged rapidly and perhaps often on Earth, despite the challenging HED conditions being commonly (and repeatedly) imposed on its surface. Thus, HED science has a role to play in understanding the early emergence of life on Earth, and perhaps for other planets more generally.

REDEFINING CHEMICAL BONDS

Low-Temperature Plasma and Electrochemistry

The electron distributions between atoms define the chemical bonds in a molecule, solid, liquid, or gas, determining the physical and chemical properties of matter. Not only do HED conditions of high pressure and temperature reshape the distribution of electrons between atoms, relative to ambient conditions, but the electromagnetic fields used to achieve these conditions in laboratory experiments also contribute to changing the electron clouds around atoms.

Large electric and magnetic fields applied in HED experiments move the electrons around within a sample, with an intense laser pulse, for example, tearing electrons away from the atoms in a form of ionization associated with preheat; light (electromagnetic radiation) incident on an atom is absorbed by the electron cloud around the atom's nucleus, and the effect is to accelerate the electrons and leave ions behind.

The essence of HED conditions is thus to form and reshape the internal electron distribution within matter, leading to the electrons and ions behaving as plasmas that are to be controlled and molded. Indeed, the 2021 plasma decadal study[1] highlights the potential for low-temperature plasma (LTP) to revolutionize chemistry, as electrons are torn off atoms and induced to form new chemical bonds. Low temperature in this case refers to the thousand-fold heavier ions moving slowly relative to the electrons, with the prospect of forming novel molecules and compounds through new kinds of chemical reactions.

The perspective of LTP chemistry offers an opportunity to use electron-ion separation in the HED regime as a means of creating new chemical bonds, and therefore new materials. This is an entirely unexplored aspect of chemistry at extremes.

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[1] National Academies of Sciences, Engineering, and Medicine, 2021, *Plasma Science: Enabling Technology, Sustainability, Security, and Exploration*, The National Academies Press, Washington, DC.

BOX 2.2
Kilovolt Chemistry

One area of current research activity is to explore the possibility of stabilizing exotic high energy density materials and properties at ambient conditions through the development of complex compounds and crystal structures.

Compression to pressures of order 10-100 TPa—atomic pressures—initiates a new kind of chemistry engaging deep, inner electrons within the atom, rather than just the outermost electrons that define chemical bonding as known at ambient conditions. At these pressures, the compression energy reaches kiloelectronvolt magnitudes, comparable to the energies of atom-core electrons.

This heretofore unexplored realm of kilovolt chemistry is now accessible to theoretical and experimental study. Theory indicates that core electrons' contributions to bonding can alter the atomic packing and physical properties of materials, stabilizing unexpected crystal structures and potentially leading to new compounds or material properties. For example, core-electron participation is found to stabilize iron in a relatively open crystal-structure geometry at tens of terapascal pressures. Also, the "noble gas" elements of the Periodic Table at ambient conditions are anything but chemically inert at high pressures.

Two examples of kiloelectronvolt-scale chemistry include (1) cold compression of atoms to the point that their core electron orbitals begin to combine and hybridize, and (2) compression at high enough temperatures that electronic transitions occur between inner atomic core orbitals or mixed core and outer orbitals (see Figure 2.2.1).

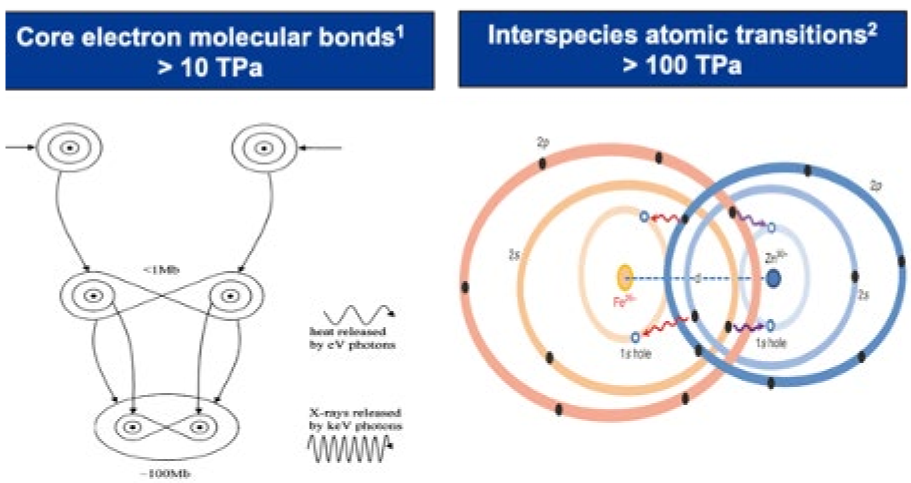

FIGURE 2.2.1 Kilovolt chemistry. *Left*: Cold compression of atoms (*top*) causes exchange first between outer electron orbitals (*middle*) and then engaging core orbitals in the interatomic bond (*bottom*). *Right*: High-temperature compression can lead to electronic transitions between core atomic orbitals, hence mixed core orbitals.

SOURCE: *Left*: Reprinted by permission from Springer Nature: F. Winterberg, 2008, "Conjectured Metastable Super-Explosives Formed Under High Pressure for Thermonuclear Ignition," *Journal of Fusion Energy* 27:250-255; © 2008. *Right*: S.X. Hu, V.V. Karasiev, V. Recoules, P.M. Nilson, N. Brouwer, and M. Torrent, 2020, "Interspecies Radiative Transition in Warm and Superdense Plasma Mixtures," *Nature Communications* 11:1989; CC BY 4.0.

TECHNOLOGY AND SOCIETAL IMPACT

Fusion in the Laboratory

An extremely pressing issue facing humanity in the upcoming decades is that of generating enough energy for sustainable prosperity. The world is in need of a plentiful, carbon-free source of energy. Nuclear fusion, the same process powering the Sun, has the technical potential to offer such an energy source.

One pathway for insight into the fusion process may be through laboratory inertial confinement fusion (ICF), and evidence of significant energy being released in ICF experiments is among the most exciting recent breakthroughs in HED science. For the first time, more energy has been produced by nuclear fusion than was directly accessible to the material being compressed. That is, self-heating due to nuclear reactions was clearly demonstrated, and the ICF sample came close to the point of ignition, defined as yielding more energy than delivered to the whole target by the laser (see Figure 2.5). This breakthrough is the result of advances in scientific understanding, computer simulation, diagnostics, industry-led manufacturing, Discovery Science programs in basic research, and more.

Both laser- and magnetic-driven ICF have seen major progress over the past decade, to the point that the onset of nuclear ignition is now being approached. The amount of nuclear energy released increases rapidly—by a factor of 10 to 100—once ignition is surpassed, thereby opening major new prospects for scientific research as well as for society.

In particular, through a renewed emphasis on fundamental science, the research community will be in a position to start optimizing ICF so as to explore its prospects as a source of energy for society. If successfully developed, fusion energy has the benefits of being carbon-free and based on readily available materials (i.e., the deuterium and tritium forms of hydrogen). It is well suited to an electric-based society, which many see as being the best aligned with future technologies and the most sustainable from resource, climate, and environmental perspectives.

Laboratory-based nuclear fusion would also provide intense sources of particles (e.g., neutrons) and a HED area of research. For example, 10-100 PPa = 10^{16}-10^{17} Pa = 100-1000 Gbar pressures are associated with nuclear fusion, up to a million-fold times the onset of the HED regime (see Figure 2.6). A new era of HED science and applications would thereby be initiated.

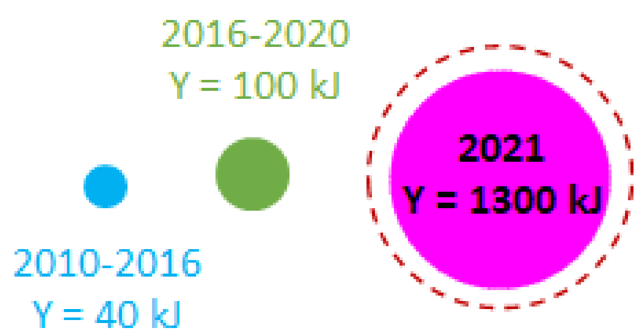

FIGURE 2.5 Energy produced by laser-driven fusion experiments have dramatically increased over the last few years, as indicated by the size (area) of circles, with nuclear output in several experiments now matching or exceeding the amount of energy delivered to the sample material (200-300 kJ). Recent experiments at the National Ignition Facility have generated up to 1.3 MJ energy yield for a total laser input of 1.8 MJ (dashed circle), approaching the ignition criterion whereby energy output exceeds the total input of energy.
SOURCE: Courtesy of Lawrence Livermore National Laboratory.

Finding: Laboratory-based ICF is experiencing major breakthroughs that can be enhanced by focusing on the underlying science.

Finding: NIF is a young facility for scientific research, with over half its diagnostics put in place in the past 5 years, showing that rapid progress can be made with suitable investment in experimental measurement and computational analysis.

Finding: NIF, Omega, and Z, the major NNSA HED laser and pulsed-power facilities, are producing breakthrough science, including through their external user programs for Discovery Science.

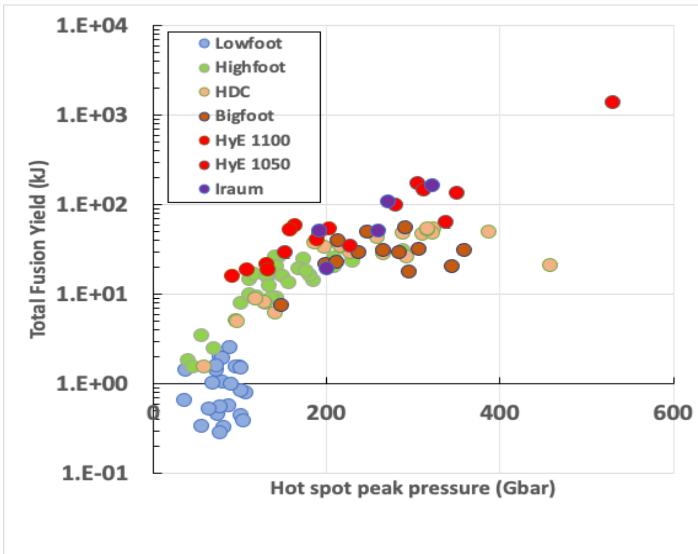

FIGURE 2.6 Energy produced by nuclear fusion is shown as a function of peak pressure achieved in inertial confinement fusion (ICF) experiments at the National Ignition Facility for different target configurations: "Low foot": low initial laser-driven shock (*light blue*); "High foot": high initial laser-driven shock (*light green*); HDC: high-density carbon (diamond) capsule (*gold*); Big foot: high initial laser-driven shock followed by large compression (*purple*); HyE: hybrid design with increased capsule radius (*red*, for 1050 and 1100 μm inner radius diamond ablators); Iraum: reshaped hohlraum design (*purple*). The energies are effectively measured, whereas the pressures are derived from indirect measurements and calculations (1 Gbar = 100 TPa = 10^{14} Pa).
SOURCE: O.A. Hurricane, P.K. Patel, R. Betti, et al., "Physics Principles of Inertial Confinement Fusion (ICF) and Status of the U.S. Program," LLNL Report LLNL-JRNL-819317-DRAFT, submitted to *Reviews of Modern Physics*, 2022.

BOX 2.3
Recent Breakthrough in Inertial Confinement Fusion

On December 13, 2022, after the present report was written and reviewed, the Department of Energy and the National Nuclear Security Administration announced that a target compressed and heated by 2.05 million joules (MJ) of laser energy produced 3.15 MJ energy due to nuclear fusion, the Sun's energy source. Carried out at the Lawrence Livermore National Laboratory's National Ignition Facility (NIF), this experiment is the first to demonstrate net fusion energy production in the laboratory, with a target gain of 1.5 (see Figure 2.3.1). The result is important as a proof of concept, and for future prospects: the amount of fusion energy released increases by powers of 10 with even slight increases in compression of the target.

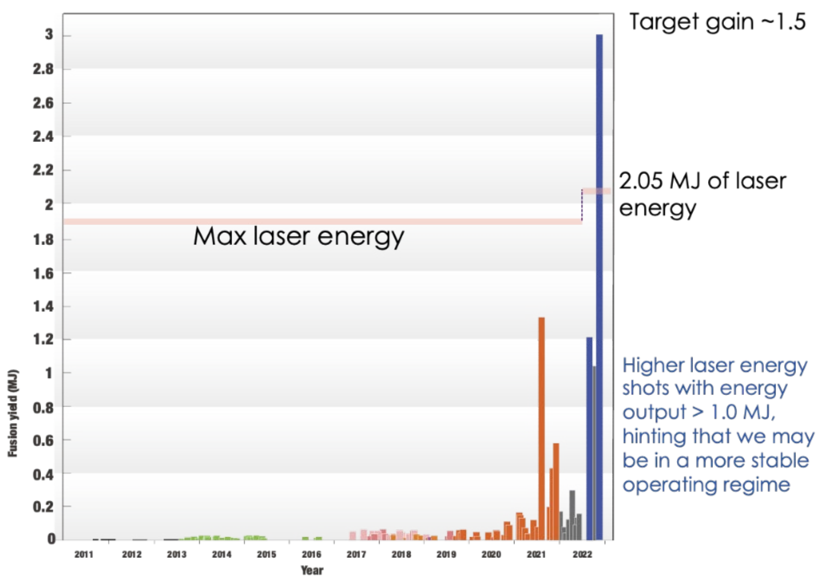

FIGURE 2.3.1 Researchers have made huge strides in producing energy from nuclear fusion in the laboratory, with the bar colors representing different design approaches used at the National Ignition Facility. Laser energy at the target was 2.05 MJ for the December 2022 record-breaking shot, whereas 1.9 MJ was the maximum in previous years.
SOURCE: Courtesy of Lawrence Livermore National Laboratory.

Targets

One of the key enabling technologies for performing HED science is the targetry, which is required in virtually all experiments. Target advancements can drive new scientific discoveries in and of themselves. Most recently, the target quality played a significant role in the ignition shot at the NIF. Highly specialized target fabrication laboratories are required, supplied by specific research groups or industrial partners such as General Atomics. Despite incredible advances in target design, fabrication, and metrology, a significant number of challenges exist for developing targets for the upcoming decade. Most pressing is the need to adapt to repetitive systems; current flagship experiments operate at a single-shot capacity, and nearly all aspects of targetry will need to be rethought. Additionally, materials such as low-density foams, amorphous high-density materials, and high-shock-impedance windows need to be developed to facilitate current experiments and enable future ones. Advances in fabrication, particularly in additive manufacturing, are set to solve numerous issues with complex, multi-component targets where joints and welds can introduce defects or leaks. Finally, metrology capabilities are needed on smaller spatial scales, and to see target composition and quality throughout the entire target. Just as there is a need for targets to be produced with

ever smaller features and surface roughness, the tools required to characterize those targets also must increase in capability.

Finding: All major facilities have extensive requirements for future target—from design, to fabrication, to metrology—particularly to adapt to higher repetition rates.

Superconductivity

Superconductivity, fascinating to physicists because this quantum effect allows for the free flow of electric currents, was for many decades limited to low temperatures (see Figure 2.7). For society at large, superconductivity at easily accessible conditions would revolutionize the economy and technologies, transforming sectors ranging from energy production and transmission to medical imaging and transportation.

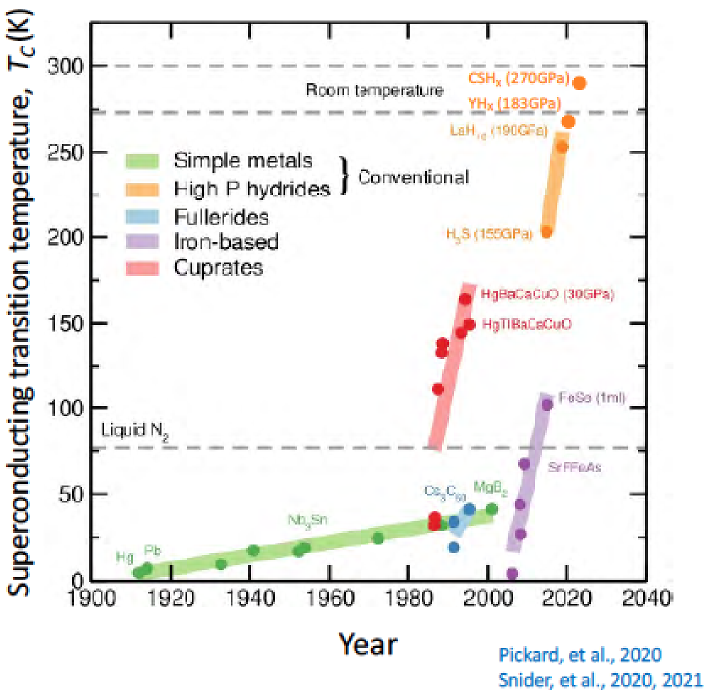

FIGURE 2.7 Materials exhibiting superconductivity—perfect conduction of electric currents—at room temperature have finally been discovered after more than a century of study. The figure shows experimentally measured superconducting transition temperatures as a function of time, with room-temperature superconductors having been discovered above 180 GPa pressure by 2020. Although currently synthesized at high pressures, research suggests that it is possible to produce room-temperature superconductors at or near ambient conditions.
SOURCE: C.J. Pickard, I. Errea, and M.I. Eremets, 2020, "Superconducting Hydrides Under Pressure," *Annual Review of Condensed Matter Physics* 11:57-76.

Room-temperature superconductors would be all-important for an electrified society of the future, so the race is on to find ways of synthesizing such metals at conditions near ambient (as has been done for diamond, for example, see Box 1.2). It is unknown if this is feasible, but the prospect exists that complex compounds containing many different elements in the types of intricate crystal structures often developed

at high pressures could have the desired superconductivity and still be made in bulk quantities at low pressures.

The significance of HED science is that it greatly enhances the quantum regime of superconductivity, with several room -temperature superconductors having now been discovered at high pressures. In particular, hydrogen-rich compounds are found to exhibit superconductivity at the highest of temperatures, consistent with current HED understanding of hydrogen itself—these crystalline metal hydrides apparently exhibit some of the exotic quantum properties expected for metallic atomic hydrogen. HED experiments guided by theory and machine learning (to handle the multi-dimensional problem of characterizing complex compounds) hold promise for this research, which is at the cutting edge of both basic science and applied technologies.

Quantum Sensors

Recent developments of quantum sensors are supporting efforts to achieve novel conditions and make new materials in HED research. For instance, nitrogen-vacancy pairs (NV centers) in diamond can be used to measure the magnetism and detailed state of stress (stress tensor) in samples contained inside diamond-anvil cells at HED pressures. Magnetism can be a key indicator of superconductivity, thus helping to characterize the high-pressure materials of interest and to provide experimental data for comparison with theory.

That these sensors can map out the stresses across samples is exciting in its own right, because shear and normal stresses can now be quantified and potentially controlled as a function of pressure and deformation. For the first time, there is experimental access to determining the ultimate strength of materials under a wide range of loading conditions, raising the possibility of fundamentally advancing understanding of how and why materials deform and break.

BOX 2.4
Extreme Ultraviolet Lithography and High Energy Density Science

High energy density (HED) experiments are extreme by nature, and yet they directly impact the modern technologies of our daily lives, from cell phones to large-scale computer systems. This is why many diagnostics use X rays, which are able to penetrate the high-density material without being affected by the strong electric and magnetic fields around the sample. The low-energy range of X rays, labelled soft X rays or extreme ultraviolet (EUV), was known to have many useful spectroscopic properties for studying HED science, but unfortunately there did not exist any effective way to manipulate this light.

This changed with the introduction of multilayer mirrors, which was the first practical high-reflectivity mirror for EUV. Now, optics could be built that manipulate EUV light, and the intense interactions of HED experiments could be imaged.

It was then realized that this was enabling technology for EUV lithography, as up to this point there was no clear path for how the semiconductor industry would move past ultraviolet wavelengths to keep Moore's Law progressing, thus preventing limitations to increased processor speeds. A talk given at a lithography conference garnered so much interest that a partnership was soon formed. Through the Department of Energy's (DOE's) Technology Transfer Initiative Program, using CRADAs (Cooperative Research and Development Agreements), Lawrence Livermore National Laboratory, Sandia National Laboratories, and Lawrence Berkeley National Laboratory, along with numerous companies, began developing EUV lithography. A virtual national laboratory was formed with investment from both industrial partners and DOE. This joint venture was crucial to success.

Critical technologies, such as imaging optics, mask coatings, and steppers, were developed and demonstrated using laser-produced light sources. Currently, the semiconductor company ASML in San

Diego, California, produces the EUV light source, which itself involves a high-repetition-rate laser plasma interaction where EUV light is collected and redirected with multilayer mirrors.

This is all derived from the HED technology developed by the laboratories and partners in the decades prior. It is highly unlikely that EUV lithography would exist today without this specific program and support. In short, HED science spun off the modern $500 billion per year computer micro-chip manufacturing industry based on EUV lithography, and the reason that the United States is home to the majority of EUV lithography tools is because of this specific program emerging from the national laboratories and the support provided by it.

ROLES OF THEORY, SIMULATION, AND EXPERIMENT

This chapter closes with a note about the complementary roles of theory, simulation, and experiment, all of which are necessary and depend on the integration of HED science featured throughout this chapter.

Two primary goals of theory and micro-scale computer simulation are to interpret the results of experiments and to predict the existence and properties of new materials, including those potentially having important technological applications.

Rigorous experiments, coupled with the kinds of advanced diagnostics detailed in the National Diagnostics Plan,[2] can validate these predictions and provide insights into how to improve theory and obtain more accurate results over a broad range of conditions—including those that are not yet experimentally accessible. There may also be cases in which experiments uncover gaps in theory, revealing unexpected new phenomena, states, or processes. In such instances, it is critical to validate and compare results from multiple theoretical and experimental approaches so as to improve existing theoretical approaches.

Rooted in quantum mechanics, atomistic theories and ab initio simulations provide a fundamental basis for advancing the scientific understanding of matter, as well as for developing new materials for society. But HED science is not only concerned with the atomic-scale properties of matter at extreme conditions. Multi-scale, multi-physics simulations that model entire experiments and applications are critical to the field's contributions to fundamental science and to applications ranging from laboratory nuclear fusion to planetary geophysics and astrophysics.

These simulations link experimental-scale predictions to the properties predicted by quantum mechanics at the microscale and to molecular dynamics, particle-in-cell, and kinetic models that can capture effects like mix, turbulence, and laser-plasma interaction. They may be hydrodynamic codes that depend on equations of states (EOS) to capture compression and bulk thermodynamic evolution of matter, and they may include radiation transport and/or non-local, non-equilibrium effects, or they may include descriptions of a material's interactions with various sources of compression and heating, such as laser absorption or magnetohydrodynamics. The increasing fidelity, flexibility, and reliability of these critical tools—and the underlying experiments—is one of the triumphs of HED science.

> Finding: The integration of approaches from theory, simulation, and experimentation is critical in the HED regimes, for which the multiplicity of time and lengths scales leads to challenges in understanding basic material properties and macroscale system behavior.

For more information about the tools and facilities used in HED science, as well as more technical information about ICF, see Appendixes B through D.

[2] S. Ross, 2020, "The ICF National Diagnostic Plan (NDP) September 2020." United States. https://doi.org/10.2172/1671177.

TABLE 2.1 Research Advances: Illustrative Examples Noted in Chapter 2

Physics and Materials: Matter Manipulation on the Quantum Scale	
Fluid hydrogen, deuterium metallized on multiple platforms	PRL 76 (1996) 1860
with application to giant planets	Science 348 (2015) 1455
	Science 361 (2018) 677
Semi-metallic crystalline hydrogen	Science 355 (2017) 715
	Nature Physics 15 (2019) 1246
	Nature 577 (2020) 631
Metallization of helium	PRL 104 (2010) 184503
	PNAS 105 (2008) 11071
Crystalline metallic oxygen characterized	PRL 102 (2009) 255503
Metallization of carbon	Science 322 (2008) 1822
Metallic oxides, silicate planetary dynamos	PRL 97 (2006) 025502
	Science 338 (2012) 1330
	Science 347 (2015) 418
Transparent sodium	Nature 458 (2009) 182
Carbon taken to TFD regime	Nature 511 (2014) 330
TPa diamond-anvil cell (DAC) experiments	Sci Adv 2 (2016) 12
	RSI 89 (2018) 111501
TPa calibration via laser- and magnetic-compression experiments	Science 372 (2021) 1063
First Gbar (10-100 TPa) laboratory measurements	Nature 584 (2020) 51
Origin and Evolution of the Solar System	
Iron opacity measured, theory and astrophysics applications	Nature 517 (2015) 56
Laboratory evidence for the magnetic field of the universe	Nat.Com.9,(2018) 591
Hydrogen-helium immiscibility: chemistry, planetary implications	Nature 593 (2021) 517
Superionic H_2O documented, implications for “ice” giant planets	Nature Phys 14 (2018) 297
First-principles equation of state (FPEOS) database	PRE 103 (2021) 013203
Applications to planetary interiors, evolution	ApJ 669 (2007) 1279
Redefining Chemical Bonds	
Kilovolt (core-electron) chemistry	PNAS 104 (2007) 9172
	PRL 108 (2012) 055505
Technology and Societal Impact	
Lawson Criterion for Ignition Exceeded in an Inertial Fusion Experiment	PRL 129 (2022) 075001
Significant fusion burn achieved in laboratory (> 1 MJ yield)	
Indirect-drive experiments as supported by simulations	Nature 601, (2022) 542-548
Direct drive yield enhancement with stat. modeling	Nature 565, (2019) 581-586
Magnetized liner ICF	POP 22, (2015) 056306
Fast ignition concept demonstrated	Nature 412 (2001) 798
Near room-temperature hydride superconductors at HED conditions (>1 Mbar)	Nature 525 (2015) 73
	PRL 122 (2019) 027001
	Nature 586 (2020) 373
	PRL 126 (2021) 117003
	ARCMP 11 (2020) 57
Successful push toward low-pressure synthesis	[Reference pending]
Quantum sensors measure stress tensor, magnetism at high P	Science 366 (2019) 1349, 1355, 1359
High-quality nanocrystalline diamond for ICF, high-pressure	[Reference pending]
Advanced X ray and particle sources	Optica 4(10), (2017) 1298
Tunable laser plasma accelerator	Nature Physics 7 (2011) 862

NOTE: ApJ, *Astrophysical Journal*; ARCMP, *Annual Review of Condensed Matter Physics*; PNAS, *Proceedings of the National Academy of Sciences*; PRE, *Physical Review E*; PRL, *Physical Review Letters*; RSI, *Review of Scientific Instruments*; Sci Adv, *Science Advances*.

3

Opportunities and Grand Challenges

OVERVIEW

The present chapter describes opportunities[1] and grand challenges capitalizing on emerging capabilities in high energy density (HED) science, as illustrated by recent breakthroughs summarized in Chapter 2. The committee develops the following three broad themes in the following pages, mirrored in Figure 3.1: (1) the *thermonuclear* regime at which densities and temperatures are high enough to sustain nuclear fusion; (2) the lower-temperature high-density range of warm dense matter, including quantum matter; and (3) more extreme, *relativistic* conditions, involving particle production and use of fusion as a basis for probing matter. Experiments and theory are intertwined in all three instances, with implications for disciplines ranging from astrophysics and chemistry to condensed-matter, materials, and plasma physics.

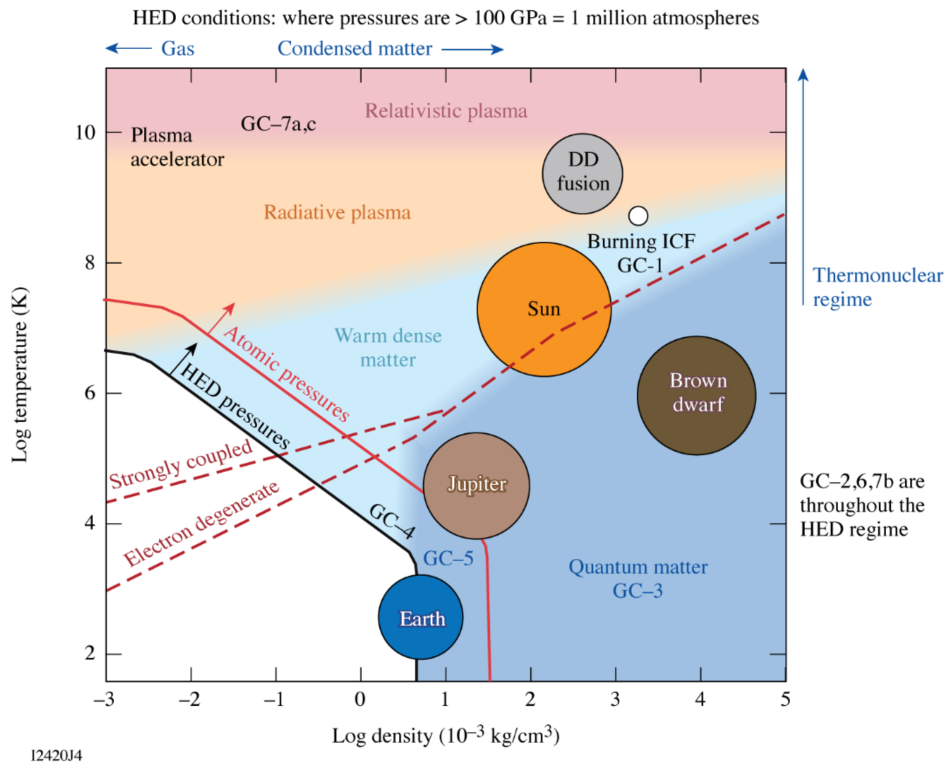

FIGURE 3.1 Extreme conditions relevant to high energy density (HED) science and Grand Challenges (GC). Density-temperature regimes of interest are distinguished by dashed curves indicating conditions at

[1] Rather than the inherently negative "gaps" noted in the statement of task, the committee chose to use "opportunities" with the intent that National Nuclear Security Administration (NNSA) and the high energy density (HED) science researchers may use these as guideposts.

which thermal energies are comparable to electrostatic charge (Coulomb) energies (strongly coupled) and to electron (Fermi) energies (electron degenerate).
SOURCE: Courtesy of G. Collins.

GRAND CHALLENGES AND OPPORTUNITIES FOR HIGH ENERGY DENSITY SCIENCE

Discoveries in HED science transform the fabric of society materialize when breakthroughs in laboratory and computational technologies can test and put to practical use the creative insights provided by theory. Recent advances in experiments, simulation, and theory allow HED research to make major new contributions to science and technology, now and in the near future. The following listing is illustrative and will no doubt be surpassed by new discoveries and innovations.

1. **Laboratory-based nuclear fusion.** ***How can burning fusion plasmas be controlled and harnessed for society's energy, security, and technology needs?*** Fundamental HED science is essential to the development of the technologies and processes required for controlling nuclear fusion in the laboratory, taking current experiments that are documenting the onset of nuclear ignition to the point of fully exploiting the output of nuclear reactions. More effective means of achieving fusion will offer a unique platform for characterizing new states of matter through experiments, simulation, and theory. (See also Appendix A for more detail on ignition.)

2. **Next-generation laboratory astrophysics.** ***Can extreme astrophysical phenomena evident from observations or predicted by theory be reproduced in the laboratory?*** HED science can leverage astrophysical observations to address major questions about the evolution of the universe, including the following: What is the nature of matter in the deep interiors of dead stars ("compact" astrophysical objects) throughout the universe? Can the background of space and time ("vacuum continuum") be broken using sufficiently intense photon densities that are now becoming available? Can we develop a quantum gravity laboratory and measure the properties of black holes ("Hawking radiation" and black-hole thermodynamics)? Can we emulate and understand cosmic accelerators? A key challenge for both theory and simulations is to quantitatively relate properties and processes at atomic, laboratory, planetary, and astrophysical scales of distance and time.

3. **Quantum materials.** ***What are the HED quantum states of matter that could lead to new classes of materials for energy transport, storage, and quantum information science?*** The discovery of room-temperature superconductivity, novel electronic phases, and predictions of superconducting superfluids at HED conditions point to new materials and phenomena that could be stabilized at everyday conditions, thereby revolutionizing technology and society. A concerted effort is required, integrating experiments and advanced simulations, including artificial intelligence and machine learning for both quantum systems and multicomponent chemistry.

4. **New chemistry.** ***Will the discovery of exotic atomic and electronic structures of matter and materials at HED conditions lead to a new chemistry of elements at conditions that occur throughout much of the cosmos?*** Experiment and theory indicate that chemical interactions at very high pressures can arise from core—and not just valence—electrons of atoms. The implications of this "kiloelectronvolt" chemistry, in contrast to the "electronvolt" chemistry of ordinary conditions, span the creation of new materials to understanding the nature of planets and other astrophysical objects.

5. **Evolution of planets and conditions for life.** ***Can we understand the conditions under which life forms and the signatures of planets on which life could emerge?*** HED science is revealing the violent impact processes by which planets form, with impact sterilization frustrating the early

emergence of life; how planetary interiors and surfaces evolve; and how magnetic fields can be produced, shielding the planet's surface from the charged particles and ionizing radiation emitted by the host star. HED experiments and simulations can provide the necessary validation of material properties used in interpreting the results from astronomical observations of planets and their atmospheres, including inferences of planetary formation, evolution, and current state. Impact processing of pre-biotic molecules also set the stage for rapid—perhaps even multiple—emergence of conditions that lead to life.

6. **Cross-cutting science and the multi-scale nature of HED science.** ***How can multi-scale theory, simulations, and experiments predict the behavior of macroscale objects and processes?*** HED science crosscuts a number of fields and connects vastly different scales of energy, distance, and time—from atomic to astrophysical. A new generation of experiments and modeling, including simulation and theory, is beginning to define the linkages between these different scales, helping to characterize the stability of inertial confinement fusion (ICF) implosions; translating microscopic viscosity estimates to magnetic dynamo processes in planets; defining the strength of bulk matter; and correlating between kinetic, thermal, plasma-wave, Coulomb, and nuclear energy scales in the warm dense matter of low-mass stars.

7. **Cross-cutting technology developments.**
a. Table-top photon and particle sources as benchtop microscopes. Many key questions in HED science can be addressed using current and emerging technologies, including compact X-ray-free electron laser (XFEL)-like sources. These provide experimentalists with nanometer spatial and femtosecond temporal resolution, thereby allowing quantitative characterization of the hot spot and confining-fuel densities inside ICF implosions, phase transition and chemical kinetics of ultra-compressed matter, new quantum electrodynamical (QED) states, and the structural complexity of new states of matter (e.g., electride solids and fluids).

b. High-repetition-rate problem solvers. Evolving today's single-shot experiments, analysis and simulations toward artificial intelligence–empowered experiments (high-repetition-rate intelligent hypothesis solvers rooted in computational inference engines) has the potential to massively increase the rate of scientific discovery. For example, the table-top diagnostics (above) and high-repetition-rate drivers will enable quantitative mapping of the multi-scale (subatomic to macroscopic) evolution of matter at HED conditions, with experiments producing the big data that empower machine learning approaches to data assimilation and discovery, especially for multi-component chemical compounds. Other key technologies for this next-generation capability include development and use of the broad-band lasers for enhanced absorption and drive, high-speed diagnostics such as the pulse-dilation-drift-tube technology, high-speed detectors based on the Pockels or Stark effect.

c. High-intensity laser sources. Through chirped pulse amplification (CPA; see also Box 3.2), light intensities of up to 10^{23} W/cm^2, with wavelengths in the vicinity of 1 μm, are now readily available. The energy density of such light already exceeds 10^{17} J m^{-3}, surpassing by a million-fold the onset of the HED regime described in this report. In interacting with matter, this large energy density represents an enabling technology for HED applications. An important frontier of research is to extend this enabling technology, for instance through the use of "plasma optics," the parametric interactions of electromagnetic waves mediated by plasma. Exploiting the fact that plasma easily withstands these intensities represents an opportunity for reaching the next factor of 1,000 increase in intensity (see Figure 3.2).

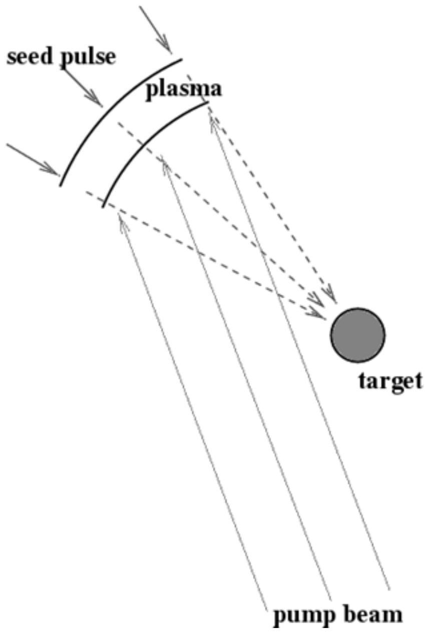

FIGURE 3.2 Through nonlinear wave interactions in plasma, a short seed pulse absorbs the energy of a long counterpropagating pump pulse twice the length of the mediating slab of plasma. The seed pulse encounters the front of the pump pulse as it enters the plasma, and the tail of the pump pulse as it leaves the plasma. The result is that nearly all of the pump pulse energy can, in principle, be captured in the seed pulse, making the short seed pulse, upon exiting the plasma slab, many times more intense than the long pump pulse.
SOURCE: V.M. Malkin, G. Shvets, and N.J. Fisch, 1999, "Fast Compression of Laser Beams to Highly Overcritical Powers," *Physical Review Letters* 82:4448-4451, https://doi.org/10.1103/PhysRevLett.82.4448.

To address these grand challenges and opportunities, as well as many of the stated goals of the National Nuclear Security Administration (NNSA) made accessible through today's technology, the committee recommends the following:

> **Leading Recommendation: To strengthen its global leadership in high energy density (HED) science and address future national needs, the NNSA should exploit and enhance the capabilities of its flagship HED facilities (e.g., the National Ignition Facility, Z Pulsed Power Facility, and Omega Laser Facility) by establishing plans over the next 5 years for (1) extending, upgrading, or replacing those facilities; (2) increasing the promotion of forefront technology development, including in high-intensity lasers; (3) enhancing academic capabilities and mid-scale facilities; and (4) broadening remote access to its major experimental and computing facilities.**

EXTREME TEMPERATURE AND PRESSURE: NUCLEAR FUSION

Fusion powers the Sun and stars, provides heat and light to Earth and has forged all of the elements we use (and are made of) through many cycles of stellar evolution. In our Sun and in a handful of laboratories on Earth, nuclear fusion happens when two light nuclei (composed of just a few neutrons and protons) get close enough together that nuclear forces overwhelm their electrostatic repulsion. As the two nuclei fuse together to form a heavier element, a small amount of mass is released as energy, following

Einstein's famous $E = mc^2$. This is in contrast to nuclear fission, which is the splitting of a heavy nucleus into lighter elements. One of the easiest fusion processes involves isotopes of hydrogen: deuterium (a hydrogen isotope with one proton and one neutron) interacting with tritium (a hydrogen isotope with one proton and two neutrons) to form a helium nucleus (alpha particle). After the fusion event, the alpha particle and the extra neutron carry significant energy; each reaction produces millions of times more energy than the typical chemical reactions that now fuel our cars and homes.

Opportunity: Harnessing Star Power in the Laboratory

A primary challenge of sparking nuclear fusion is directly related to delivering the energy required to overcome the natural repulsion of the positively charged nuclei that make up fusion fuel. The current strategy to initiating fusion reactions is to heat fusion fuel to temperatures exceeding a million degrees, forming a hot plasma that is confined for long enough that the energy from these initial reactions can be sustained. When a fusion plasma captures enough of its own fusion energy to maintain a steady temperature and produce significant energy yield from this self-heating, it is called a burning plasma. When it captures enough energy to heat itself by several more millions of degrees, thereby exponentially increasing the rate of fusion reactions, it is a plasma on its way to ignition.

The second challenge of fusion is confinement: hot plasmas are hard to confine; they expand, just as hot steam does from a kettle. And because plasmas consist of charged particles, we cannot confine them easily. Because of their large size, stars confine fusion plasmas by the sheer force of gravity. On Earth, one way to confine plasmas is to use magnetic fields, the approach taken by the magnetic fusion community. Using tokomaks (e.g., like the fusion experiment ITER), stellerators, and similar devices, a low-pressure plasma with a density a millionth that of the atmosphere at Earth's surface is heated to high temperatures and confined by stationary magnetic fields created by permanent magnets. Another way to confine a plasma is through inertial confinement, which uses an implosion to create a hot plasma with densities hundreds of times greater than familiar solid material, holding it together long enough for nuclear ignition and burn to occur. In both cases, net energy production must satisfy the Lawson criterion, a requirement that the product of the pressure (P) and confinement time (t) must be greater than about 5 MPa-seconds (50 bar-seconds).

Magnetically confined fusion experiments operate at low densities for long times, and inertial fusion experiments operate at high densities for short times; however, both must reach or exceed this simple product to produce net energy from fusion reactions. The idea of ignition is unique to inertial fusion, with fusion reactions not merely maintaining the plasma temperature over the confinement time but also leading to the runaway heating that increases the temperature and rate of fusion production, enabling efficient burn-up of the fuel.

> Finding: Recent progress approaching fusion ignition with megajoule-class lasers has validated the fundamental principles of hot-spot ignition, making the next decade a crucial time for an improved understanding, control, and use of burning plasmas from ICF.

The field of inertial fusion—unlike its cousin, magnetic confinement fusion—has strong ties to HED science. Like all HED science, it is massively multi-scale and requires designing, testing, and diagnosing plasma experiments that take fusion fuel and surrounding components from room-temperature (or cryogenic) conditions to the hot dense plasmas enabling fusion reactions. Part of this work involves finding ways to deliver the energy that can heat, compress, and control matter, which requires extensive engineering to develop suitable lasers and pulsed-power devices. A deep understanding is needed regarding how materials respond to these drivers and move through the vast temperature-density-radiation space of the HED regime. In particular, HPC is critical to accounting for the multi-scale interactions of atomic-scale properties with mesoscale and macroscale effects, such as turbulence, hydrodynamic instabilities, and sample or driver asymmetries. Also, development of new targets, with better quality control of materials and designs, may prove essential to success. Finally, inertial fusion experiments use sophisticate diagnostic

tools, including the following: imagers that characterize micron-scale features that change over sub-nanosecond time scales; neutron and X-ray spectrometers that provide detailed information about the atomic- and nuclear-scale interactions of the rapidly evolving plasmas; and radiation-hardened diagnostics for high-neutron/gamma-flux applications.

The inter-relationship of ICF and HED science is complex. ICF relies on advances in fundamental science understanding, as well as the drivers, codes, and diagnostics developed in the larger field of HED science. Different spatial and temporal scales and a variety of experimental approaches are essential, as summarized in Appendixes A and D. The prospect of limitless, safe, and clean inertial fusion energy (IFE) can be a powerful motivator for both funding and recruitment—especially in the midst of the climate crisis. But ICF also offers unique opportunities for HED science itself—the extreme temperatures, densities, and radiation fields created by an igniting plasma lead to new pressure–temperature–radiation regimes that cannot be accessed in other terrestrial environments.

Finally, inertial fusion also has deep intellectual ties to stockpile stewardship, which has enabled the United States to maintain a safe, secure, and reliable nuclear-weapons stockpile without nuclear explosion testing since 1992. Those ties have led to the present-day funding landscape in which the NNSA supports almost all of the U.S. ICF efforts, and even a significant fraction of basic HED science. while those ties have provided ICF and HED scientists with the rich intellectual legacy of the NNSA laboratories, they also can impose necessary boundaries on free and open scientific discourse (see Chapter 5 on security).

Major Recommendation: The inertial confinement fusion community should redouble efforts to focus on the underlying basic science to (1) achieve robust ignition and the maximum yield with optimal efficiency, (2) establish the best uses of laboratory burning plasmas, and (3) help identify the best path for future experimental and computational facilities. In particular, the sustainment of innovation and breakthrough research will require a careful balance between yield-producing and non-ignition experiments. Additionally, the NNSA should work with the relevant agencies (e.g., the Department of Energy's Fusion Energy Sciences and Advanced Research Projects Agency–Energy and the National Science Foundation) and private industry to leverage research in inertial fusion energy and—where possible—partner in research areas of mutual interest.

More detail about the approaches to inertial fusion currently being pursued are elaborated in Appendix A, while Appendix C summarizes key U.S. HED science facilities.

Opportunity: Opacities at Stellar Interior Conditions

Stars and their life cycle are important in nearly all areas of astrophysics. Distant galaxies are understood by way of the light from their stellar population, and stars have been instrumental in revealing the existence of dark matter and dark energy.

Experiments in progress on NIF and Z measure the opacity of oxygen at conditions relevant to white dwarfs and also to the base of the convection zone of the Sun and other main-sequence stars. Densities and temperatures can exceed 100 g/cc and 1 keV in the solar core. As there are no experimental data, only theoretical models are currently used for the opacities at these conditions.

Astrophysically relevant opacity measurements now within reach are thus important for modeling Sun-like and white-dwarf stars. Extending this density and temperature coverage will make possible extrapolation to yet more extreme conditions, such as those near the degeneracy boundary in white dwarf stars. Oxygen opacity is a dominant issue for carbon-rich white dwarfs, and such experimental benchmarks will have a significant impact on stellar and white-dwarf modeling.

Hydrodynamics and Turbulence in HED Plasma

Hydrodynamic turbulence is a universal phenomenon. It occurs at ambient conditions in high Reynolds-number flows and is also present in compressible plasma phenomena such as supernova explosions. Turbulence is caused by the unbounded and protracted growth of hydrodynamic instabilities, such as the Richtmyer-Meshkov (RM) and Rayleigh-Taylor (RT) instabilities. RT instabilities, including the transition from weakly nonlinear to highly nonlinear regimes, have been explored at HED facilities. In astrophysical settings, supernova remnants can experience RT instability, producing structure at the interface between the stellar ejecta and the circumstellar matter. Recent results from HED experiments reveal how large energy fluxes, which are present in supernovae, can affect this structure.

Relativistic Plasmas and Magnetic Fields

The transition from collisionless to collisional plasma flows holds significant potential for revealing the evolution from kinetic to thermodynamic behavior in matter. Astrophysical collisionless shocks are among the most powerful particle accelerators in the universe.

Supernova remnant shocks are observed to amplify magnetic fields and accelerate electrons and protons to highly relativistic speeds. In diffusive-shock acceleration, relativistic particles are accelerated by repeated shock crossings, a process requiring a separate mechanism that pre-accelerates particles to enable shock crossing. This is known as the “injection problem” and remains one of the most important puzzles in shock acceleration. Electrons can be effectively accelerated by small-scale turbulence produced within the shock transition (first-order Fermi process), helping to overcome the injection problem. Controlled HED laboratory experiments can now characterize the physics underlying cosmic accelerators.

Galaxy clusters are filled with hot, diffuse X-ray emitting plasma, with a stochastically tangled magnetic field whose energy is close to equipartition with the turbulent motions. In the cluster cores, the temperatures remain anomalously high compared to what might be expected considering that the radiative cooling time is short relative to the Hubble time. While feedback from the central active galactic nuclei (AGN) is believed to provide most of the heating, there has been a long debate as to whether conduction of heat from the bulk to the galaxy cluster core can help the core reach the observed temperatures. Interestingly, evidence of very sharp temperature gradients implies a high degree of suppression of thermal conduction. HED experiments are now beginning to address the problem of thermal conduction in a magnetized and turbulent plasma.

Opportunity: HED Astrophysics: Advances in Nuclear Science

The incipient conditions for HED are those at which external forces overwhelm the typical chemical forces for matter on Earth. Atomic pressures ($\sim E_h/a_B^3 \sim 30$ TPa $= 3 \times 10^{13}$ Pa) are conditions at which external forces overpower the intrinsic forces holding core electrons in atoms, thus changing the nature of atoms themselves. Nuclear pressures are those at which external forces overwhelm the nuclear forces, such as in neutron stars with pressures $>10^{30}$ Pa. Such conditions are beyond current HED facilities, but during the past decade, HED facilities have explored nuclear properties by coupling hot plasma and nuclear processes in the laboratory.

For example, cross-sections of nuclear processes measured using accelerators must be corrected for screening effects, which are dominant at collision energies relevant to nuclear processes in stellar environments, supernovae and big-bang nucleosynthesis (BBN). Laser-driven implosion experiments have been used to measure light-ion fusion cross-sections relevant to stellar and Big Bang nuclear synthesis conditions in a plasma environment. Measurements of fusion product spectra from such systems are of sufficient quality to constrain ab initio theory. Measurements of elastic scattering and 2H(n,2n)1H charged-particle breakup take advantage of the diagnostic advances in HED science to measure fundamental nuclear

processes with high precision. In fact, nuclear-plasma interactions may create populations of excited isomers in HED environments, changing the effective nuclear reaction rates.

WARM DENSE MATTER

Warm dense matter (WDM) exists at key transitions in the relative dominance of thermal energy; electron (Fermi, Coulomb, and plasmon) energies; chemical bonding energies; atomic or quantum energies; and, in many practical examples, a wide spectrum of hydrodynamic energies, from turbulent to viscous to advective (see Figure 3.1). This confluence of energy scales (1) connects processes having widely differing scales of length or time, thus requiring a multi-scale approach and (2) challenges traditional hydrodynamic or thermodynamic approximations of condensed-matter and plasma physics.

In WDM, with ionized atoms (plasmas) near solid density at temperatures below 10^2 eV, existing models tend to vary widely in their predictions for material properties, and these uncertainties are carried forward into theories, simulations, and diagnostics of experiments, as well as nature's complex, multi-scale HED systems. Creating conditions suitable for reliably characterizing laboratory experiments and material properties in this regime is a Grand Challenge.

Non-Equilibrium Models and Analysis

The vast majority of existing models and measurements assume that materials are in local thermodynamic equilibrium (LTE), meaning that time-varying and, in some cases, direction-dependent effects are not taken into account. In real plasmas, however, ions, electrons, and especially radiation are rarely characterized by identical temperatures.

In the HED regime, for example, electrons initially absorb laser- or X-ray energy, which must then be transferred to the many thousand-fold heavier ions as thermodynamic equilibrium is approached; this takes time, often much more than is available in experiments. At high temperatures, the energy of an equilibrated radiation field dwarfs the energy in ions and electrons at the same temperature, so local thermodynamic equilibrium is rarely achieved above temperatures of ~100 eV. Time-dependent modeling is thus an important aspect of understanding matter at high energy densities.

Additionally, many plasmas have non-thermal ion, electron, and radiation fields that can only be understood with energy-dependent treatments of transport. For example, non-thermal "hot" electrons can be created by laser-plasma interactions, by photoionization and Auger processes under X-ray irradiation, and by acceleration across gaps in pulsed-power plasmas. In such plasmas, the "temperature" effectively becomes direction dependent, so one can no longer use a scalar temperature to model interactions but must instead follow the evolution of energy-dependent distributions. Therefore, active diagnostics such as radiography, X-ray diffraction, X-ray absorption, Thomson scattering, fluorescence, or bombardment with particle beams are required. In addition to such measurements, high-quality models will help provide detailed information about ionic, electronic, and radiative properties and their evolution.

Opportunity: Benchmark Warm Dense Matter Experiments

While WDM is profoundly difficult to model, it is possible to produce and characterize using today's technology. The primary laboratory challenges are in ensuring spatial uniformity across the sample, independently diagnosing the plasma conditions (including any departures from thermal equilibrium) and making precision measurements of the properties of interest. Measurements are challenging because WDM is generally opaque to optical diagnostics and has low self-emission. Therefore, active diagnostics such as radiography, X-ray diffraction, X-ray absorption, and fluorescence, or bombardment with particle beams

are required, and these measurements can be difficult to interpret without high-quality models that provide detailed information about ionic, electronic, and radiative properties and their evolution.

XFELs offer a particularly appealing platform, given these diagnostic needs, and have the potential to connect strongly to data analytics and machine learning, given the enormous quantities of data that could be generated. This opens the door to new experimental capabilities—for example, characterizing the complexity of atoms' inner-shell heating that leads to profound non-equilibrium effects that challenge our best models.

Permission Pending

FIGURE 3.3 High-intensity laser beams that can now be controlled to unprecedented length and time scales enable future advanced high energy density sources *Top*: Traditional, nonlinear, Thomson-scattering configuration generates a divergent photon source (purple) by scattering high-intensity optical photons (green) from a counter-propagating electron bunch (yellow). *Bottom*: Co-propagating a high-intensity pulse along with the electron bunch, using spatio-temporal pulse shaping, significantly reduces the scattered photon divergence, increases the scattered photon power, and increases the scattered photon energies.
SOURCE: *Permission Pending*.

Whereas several advanced X-ray sources exist, many are based on traditional accelerator technologies (such as XFELs like the Linac Coherent Light Source (LCLS) or modern synchrotrons like the Advanced Photon Source) requiring significant size and cost, which limit their applications in HED experiments. There has been significant effort to put mid-scale compression capabilities (100 J to 1 KJ lasers) at these light sources, but less effort has been spent on developing new light source technologies that could potentially be used at today's large compression facilities (NIF, Z, Omega). This is a significant gap because these are the only facilities capable of generating the most extreme HED conditions, including matter at atomic scale pressures and dense plasmas with significant fusion yield. Several plasma-based approaches of producing kiloelectronvolt to megaelectronvolt X-ray photons with high-intensity lasers can potentially provide alternative approaches for generating sufficient X-ray fluences, pulsewidths, and so on for HED science experiments. Recent developments in ultrashort pulse lasers now offer unprecedented control over the trajectory of a laser intensity peak, and the distance over which it is sustained, opening to door to even more advanced HED probes (see, e.g., Figure 3.3).

Opportunity: Extended High-Accuracy Models

State-of-the-art models for WDM include density functional theory (DFT), which is considered most accurate at low temperatures, and path-integral Monte Carlo (PIMC) models, which are most reliable at high temperatures. Both can access the WDM regime, but it is not clear how results from these two different approaches can be compared.

Extending these models—or developing new models that can use experiments, PIMC and DFT as touchstones—is an important frontier for HED science. As an example, recent DFT calculations have predicted observable effects of mixing valence electronic structure in compressed transition-metal alloys, an exotic effect that would signal extreme densities forcing overlap of valence states and enabling exploration of profound coupling between electrons and photons in WDM.

This is a particularly important challenge because many material properties are interrelated. For example, electron-ion collisions determine such diverse properties as electrical and thermal conductivities, stopping power, and line broadening. Models that enforce these relationships and use them to constrain observables for comparison with data can enormously increase the impact of any single, high-precision measurement.

Opportunity: Hydrodynamic Properties

In comparison with matter in other HED regimes, warm dense plasmas are characterized by relatively high densities and low temperatures. This leads to interesting macroscopic fluid properties. For example, WDM is cold enough and practical time scales can be short enough for the plasma to be effectively inviscid. As a result, hydrodynamic turbulence can be easily generated and tends to persist. The energy contained in random hydrodynamic flows might then even be large compared to the thermal energy content.

Under compression, there are then interesting questions to ask. If a blob of plasma laden with turbulent energy is compressed to a smaller volume (see Figure 3.4), how much energy is required to compress it, and how is that energy partitioned between heating and turbulent motions? This partitioning of energy is important because it affects the rate of nuclear fusion. Nuclear fusion happens only when there is large relative velocity between the reactants, which is measured by temperature, not turbulent fluid motion in which neighboring particles tend to have small relative velocities.

The next interesting effect occurs because the viscosity of plasma is proportional to $T^{5/2}$, making it sensitive to temperature, in contrast with ideal neutral gas, which is insensitive to temperature. This sensitivity leads to a positive feedback effect. The viscous dissipation of turbulent kinetic energy makes the plasma hotter, which makes it more viscous, in turn leading to faster dissipation. This positive feedback results in what has been theoretically predicted as a "sudden dissipation effect." The sudden dissipation, with sudden increase in temperature, could result in a sudden onset of nuclear fusion or intense radiation. An important opportunity lies in experimentally verifying this and related hydrodynamic effects in WDM.

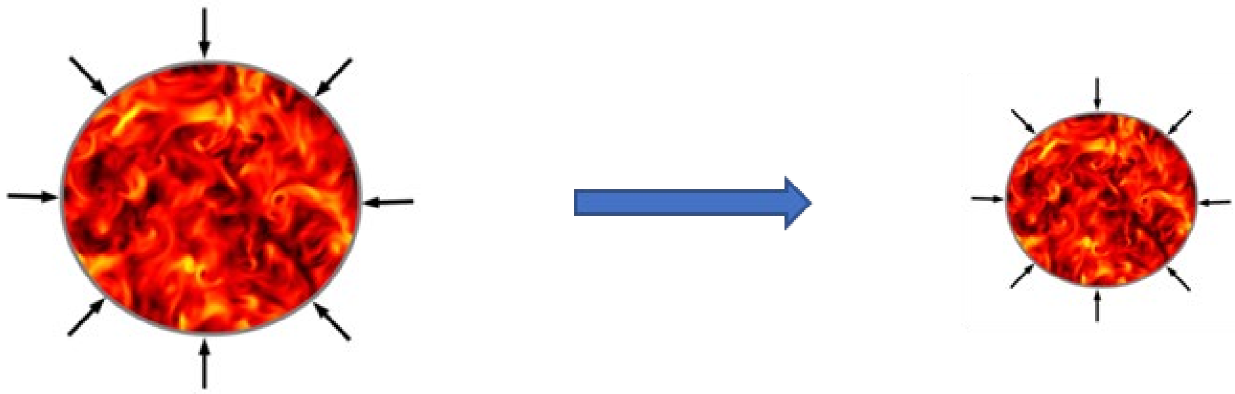

FIGURE 3.4 Compressing a turbulence-laden, inviscid plasma results in an increase in plasma temperature as well as an increase in turbulent kinetic energy.
SOURCE: Adapted from Editors' Suggestion, S. Davidovits and N.J. Fisch, 2016, "Sudden Viscous Dissipation of Compressing Turbulence," *Physical Review Letters* 116:105004.

Opportunity: Focused Multi-Scale Experiments and Modeling

Beyond the time-dependent, energy-dependent, and pressure-dependent microscale physics discussed above, the fundamentally multi-scale nature of HED science brings opportunities for focused experiments and multi-physics simulations and models that can clarify how microscale properties affect mesoscale behavior. Interesting questions include the following: How do changes in thermal conductivity affect the development of hydrodynamic instabilities? How does interdiffusion couple with turbulence and spallation that lead to material mixing across interfaces? How do rotational or turbulent velocity fields behave under compression or intense irradiation?

Here, retaining diverse experimental approaches is especially important for ensuring robust progress. Planar experiments can be driven by both lasers and pulsed power, while cylindrical and spherical geometries are most natural for pulsed power and lasers, respectively. As the system geometry can have a profound impact on mesoscale phenomena, maintaining a diversity of platforms is important for reliably transferring understanding from focused multi-scale experiments to more complex, whole-experiment systems. High-precision diagnostics of mesoscale experiments are key to extracting this understanding and have benefitted from coordinated efforts across the community to develop high-resolution instruments. In particular, XFELs like those at the LCLS Matter at Extreme Conditions end-station are among the most powerful diagnostic tools available for meso-scale imaging and X-ray diagnostics. Moreover, there is significant potential for plasma-based X-ray "lasers," generated with compact laser pumps would change dramatically the characterization capabilities for compression facilities.

> Finding: The technology of advanced, ultrashort pulsed sources (e.g., XFELs, compact plasma-based lasers, monoenergetic particle beams) when combined, for example, with one of the major compression facilities offers the potential for significant breakthroughs in understanding the multi-scale nature of WDM.

Modeling and Simulation

Advances in the field of HED science rely on a close coupling of experiment, theory, and simulation. Typically, "theory" refers to the governing equations of a particular system. For example, DFT is one of the primary atomistic theories used by HED scientists to describe compressed matter and WDM.

In the complex, multi-scale systems of HED science, few theoretical frameworks can be directly implemented using "analytic models"; instead, a majority of modeling is done using computationally intensive simulations.

Typically, "simulation" refers to a numerical implementation of a theory, or collection of theories, in a computer code. These codes can access a variety of scales or combinations of scales (e.g., a radiation-hydrodynamics code may model an entire fusion experiment, relying on constitutive data from atomic-scale simulation). A simulation based on DFT might model a handful of atoms with high theoretical fidelity, for instance, whereas a molecular dynamics simulation with empirical potentials might model thousands of atoms at a lower theoretical fidelity. Moreover, there remain challenges in radiation-hydrodynamics, extended magnetohydrodynamics (MHD), hohlraum modeling, laser-plasma intercations (LPIs), and ultra-short pulsed laser (USPL) simulations, as well as Vlasov and Focker-Planck non-equilibrium transport analyses that are ready for significant advances. Exascale computational resources are expected to allow unprecedented modeling of systems with many degrees of freedom and across many scales.[2]

Since HED experiments are typically tiny and short-lived compared to everyday length and time scales, the data obtained are usually noisy and can be difficult to interpret. Simulations are used extensively to (1) design experiments and make predictions, (2) analyze and interpret measurements, and (3) facilitate mutual testing of theory and experiments.

Understanding the reliability of simulation predictions is therefore a key facet of HED science, especially for complex systems requiring high fidelity across many length and time scales, (1) when non-equilibrium or non-local processes are significant, (2) when there is limited accuracy in existing simulations, or (3) when there is limited resolution in experimental measurements. Hence, simulation is crucial to the future of HED science, and increasing efforts in theory, simulation, and machine learning at universities and national laboratories is key to progress.

The scope of traditional HED science funding can also be broadened to support the discovery of new materials (e.g., hydride superconductors) and other new states of matter, to refine and test the predictions of both atomistic and multi-scale simulations, to extend predictive capabilities and synthetic diagnostics that enable direct comparisons to experimental observables, to explore improvements that can access more complex composition spaces, and to provide long-term support aimed at improving the underlying theory.

> Finding: A new generation of experiments and modeling, including simulation and theory, is critical to understand what is being measured and to put forward robust predictions of experimental measurements. Defining an integrated feedback loop between theory, computations, and experiments offers key opportunities for scientific advancement and technological discovery.

Future Computational Environment (Hardware and Software)

The full potential of multi-physics simulations is just starting to be realized through development, deployment, and maintenance of both theory and software. Compared with condensed-matter and plasma physics—for example, HED science is a relatively young scientific enterprise spread across different countries and institutions, some of which are in classified environments.

There is therefore an opportunity to build up a robust software community that is sensitive to the restrictions attendant to security, attuned to progress in the wider community, and aware of the great benefits of open collaboration and broad developer and user bases. Recognizing all of these factors, experience in other research communities (e.g., condensed matter) shows that open development of community codes can revolutionize the field. HED science is ripe for benefitting from similar advances.

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[2] A separate, congressionally mandated, and on-going National Academies activity has been organized on the topic of "post-exascale" computing.

At the same time, it is vital to maintain a balance between investments in software relative to hardware, to avoid researchers being unable to profit from spectacular new hardware capabilities. The NNSA has had success in co-development of codes and hardware, and this experience would be valuable in informing strategic planning for high-performance computing in basic science applied to HED science. Where possible, new codes would ideally be optimized for future heterogeneous hardware. A broad developer base that includes experts with training in modern computing architectures could enormously benefit the field.

Conclusion: Modernization of legacy computer codes, and the development of codes by the academic community, need to be systematically supported, including the development of strategies for sharing codes that leverage the experience gained by computational centers, such as those supported by the Department of Energy Basic Energy Sciences program[3] *in condensed -matter and materials science.*

Conclusion: Plans for computer hardware development and deployment after the upcoming exascale architectures would best include plans for software development based on a co-development approach, thereby assuring that the new hardware is most effectively used across the breadth of HED science.

Conclusion: Attention is needed on the possible impact of quantum computers and algorithms developed by the condensed-matter physics and quantum chemistry communities, with the possibility that most simulations using quantum architectures will be hybrid classical–quantum calculations over the next 5-10 years.

Finding: There is a significant opportunity for the development of new computational methods and algorithms, beyond optimization of codes with existing algorithms. The interface with universities is particularly important for this, and method and software developments need to be in balance with the development of new experimental techniques.

Finding: Bridging microscopic to macroscopic spatial and time scales remains a key scientific challenge that is ripe for major breakthroughs in HED science. However, it requires bridging between different communities that are methods at different scales.

Conclusion: A rigorous procedure is needed to go from the atomic scale to that of hydrodynamics and to treat non-equilibrium phenomena at the necessary time scales without sacrificing accuracy.

Machine Learning and Data Science

As has happened in many other areas of science and technology, machine learning and data science are poised to lead to great advances in HED science. For example, ML-optimization of interatomic potentials developed by computationally intensive simulations can facilitate rapid progress in calculating properties of many-body systems under conditions of extreme density and temperature. At the mesoscale, machine learning can help constrain subscale models for turbulence and mix. At the experimental scale, it can help refine target design, and more accurately determine experimental controls. There have even been initial successes in applying these techniques to ICF implosions and burn.

To date, machine learning has mostly been applied to microphysics for systems with short-range forces. However, many HED science systems have important long-range interactions. There is a need to include long-range forces and to develop efficient software to model those systems at the mesoscale in

[3] See http://miccom-center.org/centers.

order to approach and validate many-body systems and phase transitions such as metal-insulator transitions, lattice fracture, and electrides.

Optimizing experiments at high-repetition-rate facilities can provide a robust data set for machine learning, thereby supporting the development of feedback loops between theory, computation, and experiments. Strong initial efforts for integrated data collection, curation, and processing are now under way at Stanford University's LCLS, as an example. In particular, the committee encourages the following:

- Establishing databases as well procedures for data mining of large sets of measurements to investigate trends in structure–function relations, and for data processing and interpretation.
- Integrating theory and computation, key to establishing feedback loops between predictions and measurements, and to advance understanding. It is essential to define physical models to obtain robust comparisons.
- Applying machine learning for HED science, as next-generation facilities will need to produce, collect, analyze and process data at much higher repetition rates than ever, incorporating the available data from experiments and simulation into computational models. It is essential to define physical models, from atomistic to continuum, including first principles and kinetic theory, to obtain robust comparisons

Finding: Machine learning and other artificial intelligence methods are emerging as powerful scientific tools. To take advantage of this opportunity, data-driven simulation needs to be further developed, leveraging capabilities in academia, industry, and national laboratories, and experimental data and simulation results need to be made more openly accessible, with ensured peer review.

Conclusion: There is a need to ensure that standards and procedures are well defined for machine learning and artificial intelligence applications within HED science. Increased efforts to integrate theory, experiment, computation, data science, and machine learning have the potential for significant impact. Standards for machine learning and data bases are needed, with suitable efforts for adoption and adaptation by the research community.

While machine learning is a promising technology in the areas outlined above, it should not be concluded that this will replace the traditional approaches that have been needed for solving coupled, nonlinear, differential equations. Machine learning will supplement rather than replace these technologies.

Benchmarking

Benchmarking, in general, refers to establishing an independent standard that can be relied on to characterize the accuracy of any given model or experiment. Scientific communities tend to be most familiar with experimental benchmarks, with carefully calibrated, high-precision measurements of a material property (e.g., pressure, conductivity, or opacity) with rigorous uncertainty quantification are combined with independent measurements of the material state (e.g., density and temperature). These benchmarks may be few and far between; an example on the way to an experimental benchmark is the iron opacity data described above.

Codes can also be used to establish theory-based benchmarks. A recent example is given by a Simons Foundation project in which the general scientific community was invited to submit their computational results for several different, clearly defined, many-body quantum systems: the Hubbard model, a hydrogen chain, and transition metal atoms and dimers. For these systems, several different theoretical approaches obtained the same results, giving confidence that those methods were indeed mutually consistent, and allowing these methods to be used for a range of other systems. In the 2 years

since publication, the benchmark study has had a large impact on the electronic-structure theory community.

Standards are needed for science to advance, and the committee expects that a similar approach can also help validate research within HED science. The committee therefore recommends a theory-based benchmarking initiative focused within the HED community.

Finding: HED science can greatly benefit from a dedicated effort to establish combined experimental and theoretical standards and benchmarks in both measurement and computation, along with robust verification and validation procedures.

Major Recommendation: The NNSA should work with the academic and national laboratory user community, relevant government agencies, and industry to develop a high-performance computing (HPC) strategy for high energy density science over the next 2 years. This strategy should include benchmarking and the verification and validation of codes, code comparisons, the close integration of simulations using HPC with experiments, co-development of hardware and software for the research community, open-source documentation of codes and experimental results in a standardized open format (e.g., to enhance use and effectiveness of machine learning and artificial intelligence tools), and an industry-relevant implementation plan.

Major Recommendation: The NNSA and the national laboratories should, in coordination with partner science agencies (e.g., including the Department of Energy's Office of Science and the National Science Foundation), academia, and industry, set expectations for rigorous benchmark experiments that can provide solid foundations for multi-scale high energy density simulations. Particular emphasis should be given to characterizing material properties under extreme and non-equilibrium conditions, including conditions accessible at university- and mid-scale facilities, and develop a new generation of diagnostics that can take advantage of modern technology such as higher repetition rate (e.g., compact light sources) that access a range of time and length scales.

After defining a precise target benchmark, experimental and theoretical approaches can jointly publish comparisons, with data made available to the community along with full details of how the results were obtained (see Box 3.1). For code benchmarks, it is important that different methods be used for validation, and—within the same method—that different codes be used for verification (see also Box 3.2).

For experimental benchmarks, different platforms can be used to reach similar target conditions, albeit with potentially different time and length scales—for example, dynamic compression with pulsed power, diamond-anvil cells, or lasers. If agreement can be achieved, then the measured properties at the independently determined conditions can be used with confidence as a benchmark. If different results are obtained from different platforms, then the source of the disagreement could be identified. In the case of the long-standing disagreement between pulsed-power and laser-based measurements of the hydrogen equation of state, for example, both data interpretation and kinetic effects have apparently contributed to the disagreement.

Once a benchmark is established, it can be used to develop new theories and models, so as to increase confidence in multi-physics predictions using models that match the benchmark. For example, benchmark data from the Simons Foundation code comparison can be used to validate the DFT functionals or to develop machine-learned potentials and can also be used for predictions at conditions other than those benchmarked. Examples of reference data include properties of "simple" mixtures—for example, hydrogen and helium; dynamical transport properties, such as opacities or collision frequencies; and the structure factors, pressures, and compressions that inform equations of state.

Although most existing HED science benchmarks assume local thermodynamic equilibrium, the HED science community is now positioned to move toward benchmarking important non-equilibrium

processes. Such processes may include reaction kinetics; unequal electron, ion, and radiation temperatures; non-thermal energy distributions; complex mixtures; and strongly correlated systems under extreme conditions. Both uncertainty quantification of multi-physics codes and theory itself can be used to determine which materials and conditions are the most important for different HED applications.

BOX 3.1
Value of Benchmark Experiments

Rigorously controlled and independently diagnosed experiments serve to benchmark and ultimately validate theory and to motivate corrections to or extensions of theory where it is found to be lacking. Recent measurements of iron opacity made at the Z Pulsed PowerFacility offer a case in point, documenting good agreement with state-of-the-art atomic models for how iron absorbs ~1 keV X rays near the peak of the blackbody spectrum at densities slightly below those at the Sun's convection-zone boundary. Still, there is significant, as-yet-unexplained disagreement relative to theory at just three times higher density, so these experiments are being repeated at National Ignition Facility, illustrating the importance of independent platforms being available for replication and confirmation of novel findings.

BOX 3.2
Key High-Performance Computing Definitions

Verification of codes: Agreement with exact results or with results obtained using different codes. No comparison with experiment is made. The input given for the benchmark includes a set of physical quantities that uniquely specify the benchmark. Comparison of results can reflect differences in assumptions or approximations, as well as reflecting coding or numerical errors.

Validation of models: Establish the validity of approximations used in specific, well-defined physical models by demonstrating agreement of computed results with experimental measurements. This can also benefit from the comparison of computed results obtained using different physical models.

Benchmarking: Establish well-defined reference points from theory and experiment, often the key step in verification and validation.

Uncertainty quantification: Process of identifying and quantitatively characterizing the uncertainties in a set of processes based on experiment, theory and simulation.

EXTREME HIGH ENERGY DENSITY SCIENCE: BEYOND WARM DENSE MATTER AND NUCLEAR FUSION

Opportunity: Frontiers in High Energy Density Radiation and Particle Acceleration

Pair Production

State-of-the-art laser intensities of 10^{22} W cm^{-2} have energy densities on the order of 3×10^{17} J m^{-3}, a million-fold greater than the onset of HED at 10^{11} J m^{-3}. Therefore, the HED radiation regime, as accessed by high-intensity lasers for example, represents an important frontier in the realm of very HED science. This intense radiation regime may be considered interesting both because of its own unique physical processes, and because it offers an enabling technology for taking matter to extreme energy densities.

The interest stems, in part, from the fact that at high intensities, light can undergo a variety of nonlinear or parametric interactions mediated by plasma, by which the energy in light at certain

wavelengths may be converted into light at different wavelengths. At even higher intensities, exceeding the so-called Schwinger limit, matter-antimatter pairs may be created. A matter-antimatter plasma, comprising electrons and anti-electrons (positrons), is thought to be found in the atmospheres of pulsars and other astrophysical settings. When electrons encounter positrons, there is mutual annihilation of the electron-positron pair, releasing a large amount of radiation. Conversely, pairs of electrons and positrons are produced in the laboratory using very-high-intensity radiation sources.

To date, only small amounts of electron-positron pairs have been produced in experiments, however. An important frontier for research in HED science is to produce sufficiently many electron-positron pairs in the laboratory in order to observe the collective interactions of a large number of pairs such as occur in pulsar atmospheres. This quantum electrodynamics (QED) plasma regime, comprising an electron-positron plasma, features both strong-field quantum and collective -plasma effects. Researchers have a good idea of what these collective effects might be, because they expect a single positron to respond to electric and magnetic fields as if it had the electron mass but a positive charge. But until these collective effects are demonstrated in the laboratory, it is impossible to be sure there will be no surprises.

Figure 3.5 shows progress in achieving such a state of matter, from creating just a few positrons in the laboratory in 1996, to suggestions and simulations of reaching the QED plasma regime. Note that the energy densities involved are quite high. To reach the QED critical field for pair production, a 50 GeV electron-beam collides with a 10^{18} W/cm^2 laser pulse. The e-beam has energy density of about 10^{15} J m^{-3}, and the laser has energy density of about 10^{13} J m^{-3}. However, energy is frame-dependent, so in the relevant frame of the e-beam, the laser has energy density of about 10^{23} J m^{-3}, close to the Schwinger limit for pair production. In case (c) of Figure 3.5, where a pair plasma is simulated, the 30 GeV e-beam has a density of about 10^{20} cm^{-3}; 50 MeV pairs are created at a density of about 10^{22} cm^{-3}, so the pair energy density is near 3×10^{18} J m^{-3}.

These energy densities can be compared to the HED science onset at 10^{11} J m^{-3}; ICF energy densities of about 10^{17} J m^{-3}; or magnetic fusion energy densities of about 10^{6} J m^{-3}. They are well into the HED regime, and the opportunities of this high-radiation-energy-density regime are addressed in other reports, such as that of the Brightest Light Initiative. The present report therefore focuses on HED involving matter rather than light, yet the committee emphasizes the fundamental importance of research on HED radiation fields.

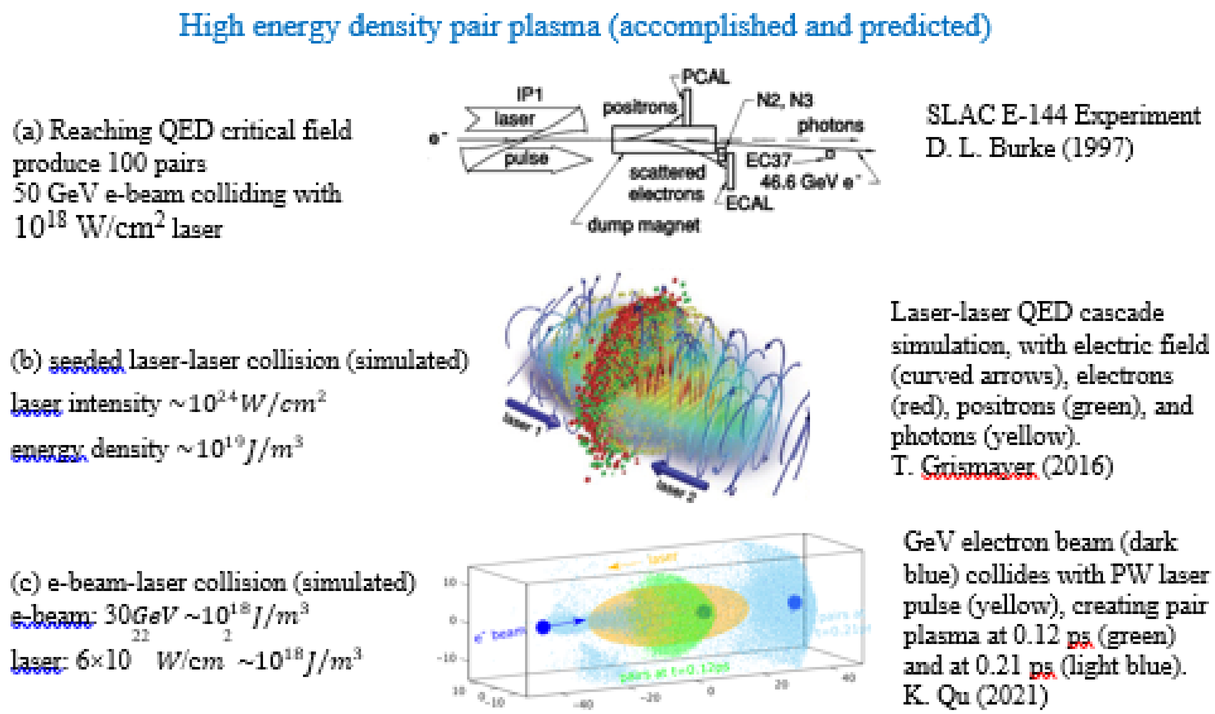

FIGURE 3.5 Producing high energy density matter-antimatter plasma was accomplished by (a) reaching critical field and producing 100 pairs (1997); (b) simulating laser-laser quantum electrodynamics (QED) cascade (2016); and (c) simulating observable collective interactions in e-beam-laser QED cascade (2021). Many other examples and recommendations of this regime are described in the Bright Light Initiative Report and thus not discussed in detail here.
SOURCE: R. Falcone, F. Albert, F. Beg, S. Glenzer, T. Ditmire, T. Spinka, and J. Zuegel, 2020, *Workshop Report: Brightest Light Initiative (March 27-29 2019, OSA Headquarters, Washington, D.C.)*, Office of Scientific and Technical Information, Department of Energy, Washington, DC, https://doi.org/10.2172/1604161.

Interest in the HED radiation regime additionally stems from its role as an enabling technology for future experiments. In particular, the next factor of a thousand in laser intensities can be developed in order to address the following: Is there completely new physics to explore? Can one separate out applications for different wavelengths? Are there robust fusion ignition schemes enabled by such high energy or intensity capabilities?

At present, only visible light can reach the necessary high intensities, through chirped pulse amplification (CPA). To amplify shorter-wavelength (e.g., UV) light requires free-electron lasing or plasma-based amplification methods. For the next factor of a thousand or so in laser intensity, which is required to reach the Schwinger limit to produce antimatter, one can imagine compressing and focusing to a cubic wavelength either megajoules in the optical regime or millijoules in the X-ray regime. In that case, the technology would likely rely on plasma-mediated approaches, such as illustrated in Figure 3.3.

Still, the present generation of lasers is impressive in its own right. New short-pulse kilojoule, petawatt-class lasers have recently come online and are being coupled to large-scale, long-pulse facilities. These short-pulse lasers also happen to reside in a unique laser regime: high-energy (kilojoule), multi-picosecond pulse-lengths, and large (tens of microns) focal spots, where their use in driving energetic particle beams is largely unexplored.

Target-normal sheath acceleration (TNSA) at the Advanced Radiographic Capability (ARC) laser at NIF has accelerated protons up to 18 MeV using laser pulse lengths exceeding 1 ps and quasi-relativistic

(~10^{18} W/cm^2) intensities, for instance. This is indicative of a process that sustains electron acceleration over multi-picosecond time scales and allows for proton energies to be achieved far beyond those of TNSA at such modest intensities. The characteristics of the ARC laser allow for the investigation of one-dimensional (1D)-like particle acceleration.

Astrophysics

Relativistic extragalactic jets are of high interest, as astrophysicists try to understand how these jets can be accelerated to Lorentz factors of several tens and how they can be so sharply collimated (see Figure 3.6a). The answers are thought to be intimately related to the mechanisms of jet launching, which are still not understood. The dynamics and creation mechanisms behind gamma-ray bursts (GRBs) are also enigmatic. One long -standing GRB model by Meszaros and Rees posits that a black hole "engine" generates a relativistic outflow with multiple internal shocks (see Figure 3.6b). In the rest frame of the observer on Earth, one can see the emissions of the multiple internal shocks as well as the forward shock. Given that they are occurring in a reference frame moving relativistically toward Earth, these emissions are shifted to gamma-ray wavelengths.

These high-energy phenomena demonstrate the need for experiments to test our understanding of relativistic plasma astrophysics. Notably, relativistic electron temperatures can now be produced and measured in subrelativistic laser-plasma experiments, suggesting great promise for breakthroughs in laboratory astrophysics.[4]

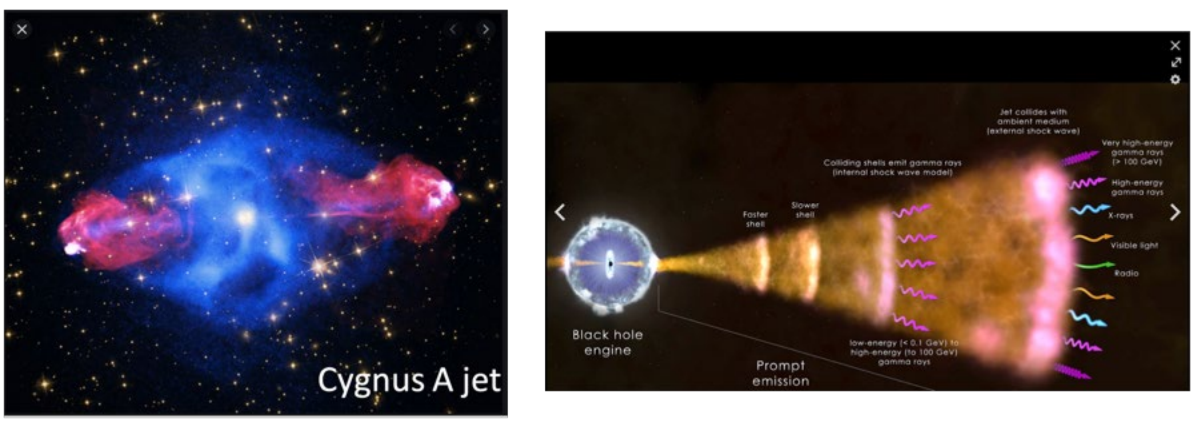

FIGURE 3.6 (a) An astronomical image of the Cygnus A jet, at a distance of ~760 million light years from Earth. (b) Artist's concept of the shocks formed in relativistic jets from ultrahigh-energy supernova explosions and/or a black hole engine that are thought to be the source of the gamma rays in "long" gamma-ray bursts (GRBs), at least in the framework of the "fireball model" of long GRBs.
SOURCES: (a) A. Klesman, 2019, "This Supermassive Black Hole Sends Jets Ricocheting through Its Galaxy," *Astronomy*, February 18, https://astronomy.com/news/2019/02/this-supermassive-black-hole-sends-jets-ricocheting-through-its-galaxy. (b) D. Byrd, 2019, "Epic Cosmic Explosion Detected via Faster-Than-Light Particles," *EarthSky*, November 24, https://earthsky.org/space/jan-14-2019-gamma-ray-burst-brightest-so-far.

[4] See Williams (2020, 2021).

Conclusion: There is a great opportunity for discovering the behavior of HED matter in extreme fields, including radiation and velocity as well as temperature and density.

Opportunity: Nuclear Reactivities in HED Matter

Astrophysically relevant nuclear reactions are just now beginning to be studied using inertial confinement fusion (ICF) implosions on NIF and Omega. These capsule implosions can be used to study plasma nuclear reactivities.

Initial studies focus on key reactions (e.g., T(t,2n)α, T(3He,np)α, and 3He(3He,2p)α), the goal being to explore thermonuclear reaction rates and fundamental nuclear physics in stellar-like plasma environments. Further goals are to push this new frontier of plasma nuclear astrophysics into unique regimes not reachable through existing platforms, with thermal ion velocity distributions, plasma screening, and low reactant energies.

HED science facilities also provide a unique capability of studying neutron-induced nuclear cross sections in an HED physics environment. In the s-process, low-lying short-lived excited states can thermally be populated in stellar plasma environments through nuclear excitation by electron capture or transition (NEEC or NEET), which may significantly alter the neutron absorption rate in branching point nuclei where such rates are comparable to their beta-decay rates, leading to altered population of predicted universal isotopic abundances. Furthermore, these processes can occur on the highly excited states produced by neutron absorption reactions before gamma emission, effectively "hijacking" an (n,γ) reaction midway through completion. As there are currently no existing capture-rate measurements on plasma-excited nuclei, the state-of-the-art HED science facilities are in a unique position to provide data of the underlying physics governing these processes. Exploding pushers are used as a source of high-yield, low-areal-density fusion products at the NIF to study nucleosynthesis relevant to astrophysics. Future work at still higher compression energies than those enabling kiloelectronvolt chemistry may enable the study of quantum nuclear (pycnonuclear) reactions in which the cold compression overlap of nuclear wave functions gives rise to nuclear fusion (see Figure 3.7).

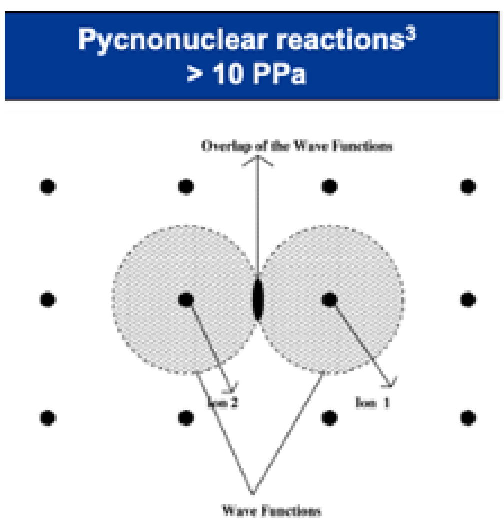

FIGURE 3.7 Pycnonuclear reactions, nuclear reactions enabled by the quantum overlap of the nuclear wave functions may be accessible in the laboratory in future years. While the required densities are challenging with today's facilities, reaching toward them might be a candidate for the enhanced drive energy available from fusion ignition implosions in the laboratory.
SOURCE: S. Son, N.J. Fisch, 2005,"Pycnonuclear reaction and possible chain reactions in an ultra-dense DT plasma," Physics Letters A 337(4–6): 397-407, https://doi.org/10.1016/j.physleta.2005.01.084..

BOX 3.3
Serendipity and Science: Chirped Pulse Amplification

Donna Strickland

In the 1980s, I was an international student at the University of Rochester and had the opportunity to carry out my Ph.D. research at the Laboratory for Laser Energetics. My supervisor was Gerard Mourou, and he led an ultrafast laser group. My research project was about finding a way to generate coherent extreme ultraviolet (XUV) radiation through high order harmonic generation, where an atom momentarily absorbs the energy of a large number of photons and then emits this energy as a single photon having the energy equal to the sum of the photon energies absorbed. To do this project, we were going to need a very intense laser to force the interaction between the ions and a large number of photons, and such a laser did not yet exist. Gerard and I developed a new laser technology, now known as chirped pulse amplification (CPA).

Before this time, there were short-pulse lasers and high-energy lasers, but you could not amplify the short pulses in the high-energy amplifiers. When it was tried, the amplifiers were damaged. It turned out that nonlinear optical processes were happening inside the laser amplifier because of the high laser intensity, given by the total energy in the pulse divided by the beam area and divided by the pulse duration in time. This means the shorter the pulse, the higher the intensity. This high laser intensity is what we wanted for the experiments and future applications. We just didn't want it in the laser amplifier itself. CPA got around this problem by first stretching the duration of the short pulses, and then amplifying the long, lower-intensity pulses. After amplification, the high-energy pulses are compressed back to their short-pulse durations, yielding the high-intensity pulses needed for the applications.

By the time we developed CPA, high-order harmonic generation had already been unexpectedly observed up to the 33rd order. My Ph.D. project needed to be changed and, along with Professor Joe Eberly and his student Steven Augst and a visiting Professor See Leang Chin from the Université Laval, we studied multiphoton ionization. Because the laser intensity was now so high, the ionization process turned out to no longer follow the expected multiphoton process, but rather could be understood classically as the large optical wave tipping over the energy well the electrons were held in, allowing the electrons to escape the well.

My Ph.D. research project is a great example of how a basic science study can lead to new technologies being created, and those new technologies then opening up new areas of basic science. With the new type of laser ionization, that occurs only at the focal spot of a high-intensity laser, clear objects like the cornea of your eye or the glass parts used in things like cell phones can now be machined.

Donna Strickland and Gerard Mourou received the Nobel Prize in Physics in 2018 for their development of chirped pulse amplification.

4

Human Capacity

A variety of career pathways and a broadly educated technical and scientific workforce is essential to advancing science, and its contributions to the nation and the world at large. Training, recruiting, and retaining a strong and diverse high energy density (HED) science workforce offers the key to developing the field, engaging universities and other educational institutions, national laboratories, and industry.

The objective is to sustain the discipline's strongest asset, its people. Now is therefore a crucial time to redouble focus on building excellence through diversity, equity, inclusion, and accessibility (DEIA) across the scientific research enterprise.

The committee considered the current state of the HED science workforce primarily through engagement with researchers in the field. This was accomplished through virtual town halls and facility site visits. (See sections "Site Visits of HED Science National Laboratories," "Additional Input-Gathering Sessions," and "Requests Sent to National Laboratories" in Appendix F for more detail.) Additionally, the committee's leading recommendation on the topic of HED science career pathways is at the core of the message developed throughout this chapter:

> **Leading Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should (1) broaden its current programs for achieving excellence through diversity, equity, and inclusion while improving workplace climate and (2) develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, such as for collaborators internationally, and with academia and the private sector.**

UNIVERSITIES AND EDUCATIONAL INSTITUTIONS

Current State of Education and Health of Workforce

Heterogeneous Education and Training

Many students who pursue research in HED science are introduced to the field through a connection with one of the National Nuclear Security Administration (NNSA) laboratories, either through a graduate or undergraduate program, or through a collaboration with their faculty advisor. In addition to direct engagement with the national laboratories and through faculty advisors, current outreach efforts could be fruitfully expanded, as HED science is an emerging field of study and offers exciting career prospects.

Students entering HED science have different backgrounds and majors—from aerospace, electrical engineering, and nuclear engineering to astrophysics, chemistry, materials science, and physics (see Box 1.4). One might even say that researchers come together from their respective fields and learn HED science on the job. While this provides an intellectually diverse workforce, the field also benefits from explicit teaching of cross-disciplinary topics in HED science. Many campuses, including those designated as minority-serving institutions (MSIs), do not have adequate resources for teaching classes relevant to HED science.

Indeed, few options often exist for HED coursework, and faculty are spread out across many departments. Students can still be educated in HED science through summer schools (e.g., those offered by

University of California, San Diego, and the University of Michigan), conferences sponsored by the American Physical Society (APS) and other professional societies, user-group meetings, and collaborations with NNSA laboratory scientists.

BOX 4.1
Multiple Pathways to Science and Careers: Relation Between High Energy Density Science and Stockpile Stewardship

High energy density (HED) science, fascinating in its own right, is linked to national security applications, including through stewardship of the nation's nuclear-weapons stockpile. Nuclear-explosion testing documented "cliffs" in performance, at which small changes in a test could result in complete failure of an otherwise successfully designed experiment. The essence of the science is to fundamentally understand these dramatic changes in performance.

Performance cliffs are present in many other domains, such as laboratory-based inertial confinement fusion (ICF), and major progress toward ignition in the past year has underscored the importance of maintaining a strong focus on HED science foundations. In order to further advance ICF, the community needs to systematically study HED plasma in conditions relevant to ICF, emphasizing the "science" in science-based stockpile stewardship.

Progress in fundamental HED science, including through international collaborations, is helping to refine our understanding in these domains, ultimately enabling high-fidelity predictive modeling of complex, multi-scale systems. In turn, achieving the Grand Challenge of robust, reproducible, laboratory-based nuclear fusion will open new vistas in the field of HED science, allowing researchers to create new extremes of densities, temperatures, and radiation fields in controlled and predictable ways. The National Nuclear Security Administration's investments in this domain are already yielding important returns as demonstrated, for example, by recent breakthroughs in ICF energy output.

Focus on Programmatic Work

Once they are pursuing research in HED science, students perceive it as an exciting field with broad possibilities, due to scientific novelty, Grand Challenges, and the ability to work with teams of experimentalists, theoreticians, and computer scientists. While they are enthusiastic about pursuing a career at NNSA laboratories, students may be less attracted by programmatic work than by basic science and associated applications, such as astrophysics, materials chemistry, or fusion energy.

Job Security

Job security, especially for international students, is also a concern, as hiring into the national laboratories may be explicitly restricted. Moreover, some early career researchers are concerned that working at NNSA laboratories will not provide them with sufficient time to perform and publish open research with rigorous peer review.

Other Barriers for Student and Postdoctoral Researchers

Barriers do exist to the academic development of students and postdoctoral researchers within NNSA facilities, including through external collaborations. Because of the conservative approach taken with regard to programmatic research, numerous impediments to sharing and presenting data exist even in fundamental research areas. For example, data sets can be difficult to share with university and outside collaborators. Many students report having difficulties or being unable to attend scientific conferences, due

to delays and other obstacles in their presentations or publications being approved for use outside the national laboratories. Academic partnerships offer a primary recruitment mechanism for NNSA's workforce, yet these restrictions can create impediments.

> Finding: Although young scholars, from graduate students and postdoctoral researchers to early-career staff, remain interested in NNSA facilities and resources and are highly motivated to pursue careers in HED science, a number of factors present barriers to recruitment or retention: cost of living; lack of transparency over job requirements and career prospects; restrictions on scientific collaborations; and increased competition from industry, compounded by alternative options for careers, among others.

> *Conclusion: Postdoctoral and similar early-career positions offer a critical source of HED scientists for NNSA laboratories and academia and deserve attention in order to enhance their effectiveness as a recruitment tool for top talent.*

Diversity, Equity, and Inclusion Limitations

As in other areas of research, diversity of scientific ideas and disciplines are essential to maximizing the impact of HED science research. Like many science, technology, engineering, and mathematics (STEM) fields, the HED science community does not match the demographic diversity to which it aspires, whether with respect to gender, race, ethnicity, or other underrepresented identities. This lack of representation is self-reinforcing, as students and early career researchers who feel unwelcome tend to leave the field; additionally, skilled technicians and support personnel—who understand how to make facilities operate—often wear out under a lack of opportunity. Most of the NNSA laboratories are aware of these concerns, but efforts remain fragile.

Best practices in DEIA, including those associated with HED science, ought to be identified as a model for NNSA and the national laboratories. Professional societies such as American Association for the Advancement of Science, the American Geophysical Union (AGU), and APS offer numerous resources, for example. In short, there is an opportunity to build a diverse, equitable, inclusive, HED science workforce through an improved workplace climate.

> Finding: As a recently emerging field of study, HED science has an opportunity to achieve excellence through leadership in diversity, equity, inclusion, and accessibility.

BOX 4.2
Diversity, Equity, Inclusion, and Accessibility and Managerial Commitment

Although training courses; diversity, equity, inclusion councils; and talent organizations are necessary, these alone are unlikely to enable the national laboratories or the broader research community to achieve their aspirations for excellence through diversity. Managers make hiring decisions, provide career development opportunities, and ultimately determine the long-term makeup of the workforce and the workplace climate in which employees contribute to science and their institution.

Progress therefore hinges on managers ensuring

- Clearly communicated expectations,
- Well-designed processes to mitigate bias in hiring,
- Monitoring these processes to ensure they are working, and
- Ensuring opportunities for career development and success.

When well-documented egregious behavior occurs, managers must make—and implement—the difficult decisions regarding discipline. As a former national laboratory director put it, “Appeals to the valuable contributions made by individuals who engage in unacceptable behavior are no more relevant in these cases than they would be were the individual to test positive for drugs.”

The committee is pleased to see continuing efforts at the national laboratories on this front and recognizes that realizing the potential of careers requires a long effort. Progress here will be the result of continuous, consistent, management commitment.

BOX 4.3
Changing the Culture Through “Moments That Matter”

The results of a culture inventory survey at Lawrence Livermore National Laboratory pointed out that there are opportunities to improve constructive cultural behaviors, and at the same time reduce aggressive and passive behaviors that undermine workplace culture and climate.

The resulting Moments That Matter program includes workshops designed to train all employees to model specific behaviors that can improve the culture at work (see Figure 4.3.1). These workshops typically involve up to 20 participants in order to create a critical mass aimed at consistently demonstrating the behaviors that help the laboratory become more effective than ever in its work.

Participants review the culture inventory reports, so that they fully understand what behaviors the laboratory is trying to change and why. It is helpful to talk about scenarios experienced by the participants, and as such, participants are asked to provide or bring examples of situations in which people were behaving inappropriately. Consistent leadership behavior in critical moments sends a message to the employees regarding acceptable and unacceptable behavior, and it requires leadership to act quickly and constructively to redirect aggressive and passive behaviors. Hence what constitutes problematic behavior, and how to correct it—both need to be well defined and well known by the employees.

Participants learn how to recognize and respond, in the moment, when they witness or hear of situations, events, or critical incidents that require attention. They learn a model for action and work together to develop and practice responses that constructively reset those behaviors.

FIGURE 4.3.1 "Moments That Matter" workshop hosted at Lawrence Livermore National Laboratory (before the COVID-19 pandemic).
SOURCE: Courtesy of Lawrence Livermore National Laboratory.

In short, misconceptions about the field can lead to under-estimating the opportunities in HED science and NNSA's work. NNSA headquarters and researchers can help correct this by highlighting the key advances of HED science, along with the field's Grand Challenges and opportunities for the future.

Recommendation: The NNSA should take steps to enable institutions working on high energy density research to (1) assess the climate; (2) get help from subject-matter experts to make explicit and quantifiable diversity, equity, inclusion, and accessibility (DEIA) goals; and (3) implement and ensure achievement of these DEIA goals.

CURRENT SUPPORT FOR RESEARCH AND EDUCATION

Several programs provide opportunities and funding for students and faculty to engage with HED science at NNSA laboratories:

- Department of Energy (DOE) science undergraduate laboratory internships
- NNSA Stockpile Stewardship Academic Alliances Program (centers of excellence, student fellowships, university grants program)
- NNSA Minority Serving Institution Partnership Program
- Partnerships and collaborations directly funded by NNSA laboratories
- DOE–National Science Foundation (NSF) partnership in plasma science
- DOE Fusion Energy Science–NNSA partnership in High-Energy Density Laboratory Plasmas
- Early career programs (DOE Office of Science and NSF, but not NNSA)
- National Laser User Facilities (NNSA)
- HED-related NSF centers (i.e., NSF Physics Frontier Centers)
- Department of Defense (DoD) programs at Air Force Office of Scientific Research, Defense Advanced Research Projects Agency, Defense Threat Reduction Agency, and Office of Naval Research, for example

Many of these funding mechanisms do not provide cycles that match graduate student timelines of 4-5 or more years, and may fail in encouraging students to commit to the field. This can have particularly keen consequences in disciplines explicitly pursued in only a few university programs (e.g., pulsed power,

atomic physics). In addition, many of these funding mechanisms seem to be underutilized or not well known across NNSA facility leadership.

Finding: The NNSA does not have an early career program for junior faculty, as is common in other areas, which limits awareness of the field and facilities.

Recommendation: The NNSA should support more internships, postdoctoral opportunities, faculty visitorships, and early career programs in high energy density science, coordinating across the NNSA in a manner similar to that supported by the Department of Energy's Office of Science.

NATIONAL LABORATORIES AND HIGH ENERGY DENSITY FACILITIES AT EDUCATIONAL INSTITUTIONS

While the NNSA national laboratories and related HED facilities are not all educational institutions by design, their internships, mentorships, outreach, and collaborations with university departments are key components of (1) developing career pathways for HED science and (2) attracting, training, and retaining the HED workforce for NNSA. This is most effectively accomplished through strong collaborations with academia, other government agencies (NSF, in particular), and international organizations. Despite a handful of targeted programs, many of these efforts are undertaken by national laboratory scientists without explicit funding or recognition.

Workforce development begins with undergraduate students; attracting young people to science even starts as early as grades K-12. For this reason, national laboratories are taking a two-pronged approach: educating the community with outreach programs for schools and public lectures and providing internships for undergraduate students. Facilities immediately co-located with universities, such as Stanford Linear Accelerator Center (SLAC) and Laboratory for Laser Energetics (LLE), give access to a large pool of students, which is beneficial to growing the field by exposing them to HED science before graduate school.

However, with the mission-driven nature of their work, laboratory employees are often confronted by a lack of structured support and recognition for mentoring students. There is consequently a shortage of mentors and advisors for student interns at national laboratories.

Figures 4.1 through 4.3 show the enrollments during 2015-2021 in undergraduate, graduate and postdoctoral HED science academic programs, respectively, at Los Alamos National Laboratory (LANL), LLE, Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), and SLAC. From the committee's point of view, these figures document a variable flow of interns and postdoctoral researchers to these facilities. As seen in Figure 4.1, the numbers of undergraduate interns at the facilities have been consistently strong for LLE and have shown marked improvement over the past 3 years at LLNL. Being located on the campus of the University of Rochester is a great advantage for LLE. As for LANL, SNL, and SLAC, there is clearly an opportunity to increase the numbers. In the case of LANL, more user access time at the other facilities could improve the situation. At SLAC, the administration stated that there is a need for more senior research advisors for the students.

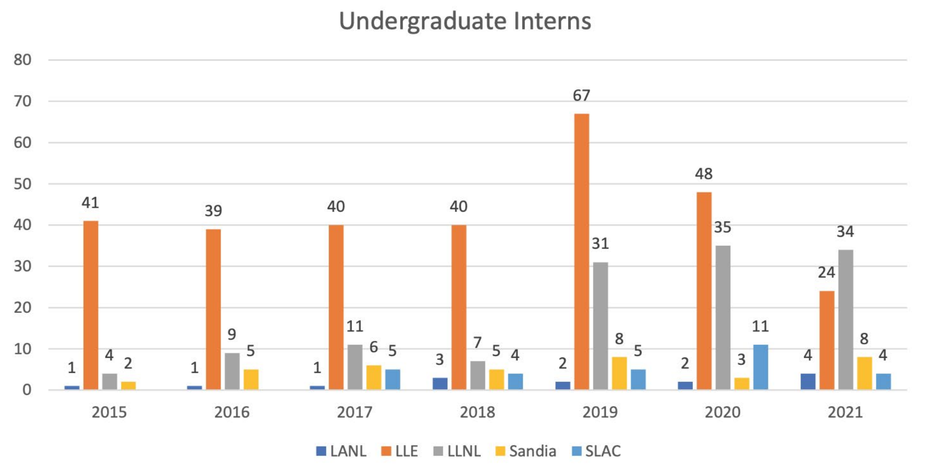

FIGURE 4.1 Enrollments of undergraduate interns at the National Nuclear Security Administration/Department of Energy high energy density facilities—Los Alamos National Laboratory (LANL), Laboratory for Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (Sandia), and Stanford Linear Accelerator Center (SLAC). The numbers of undergraduate interns at the facilities have been consistently strong for LLE and have shown marked improvement over the past 3 years at LLNL.
SOURCE: Data from LANL, LLE, LLNL, Sandia, and SLAC.

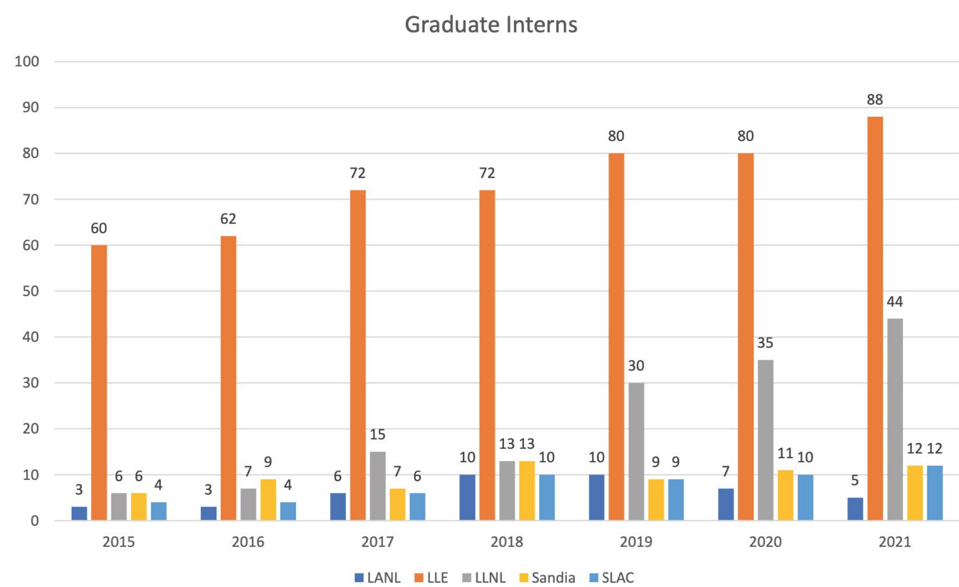

FIGURE 4.2 Enrollments of graduate interns at the National Nuclear Security Administration/Department of Energy high energy density facilities—Los Alamos National Laboratory (LANL), Laboratory for Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (Sandia), and Stanford Linear Accelerator Center (SLAC). Just as for the undergraduate interns, LLE enjoys access to many potential graduate interns, and thus its numbers are strong.
SOURCE: Data from LANL, LLE, LLNL, Sandia, and SLAC.

Figure 4.2 shows the number of graduate interns that the facilities hosted during 2015-2021. Just as for the undergraduate interns, LLE enjoys access to many potential graduate interns, and thus its numbers

are strong. The numbers have also been strong at LLNL, and there is room for improved numbers at the other facilities.

Figure 4.3 shows the number of postdoctoral fellows that the facilities hosted during 2015-2021. Over the last 3 years, the LLNL numbers have been quite strong. At SLAC and LLE, the values are good, while there is a need to increase the numbers at LANL and SNL. The numbers at LANL show a decreasing pattern over the last 3 years. Increased user access to off-site national facilities may also assist LANL in attracting additional postdoctoral researchers.

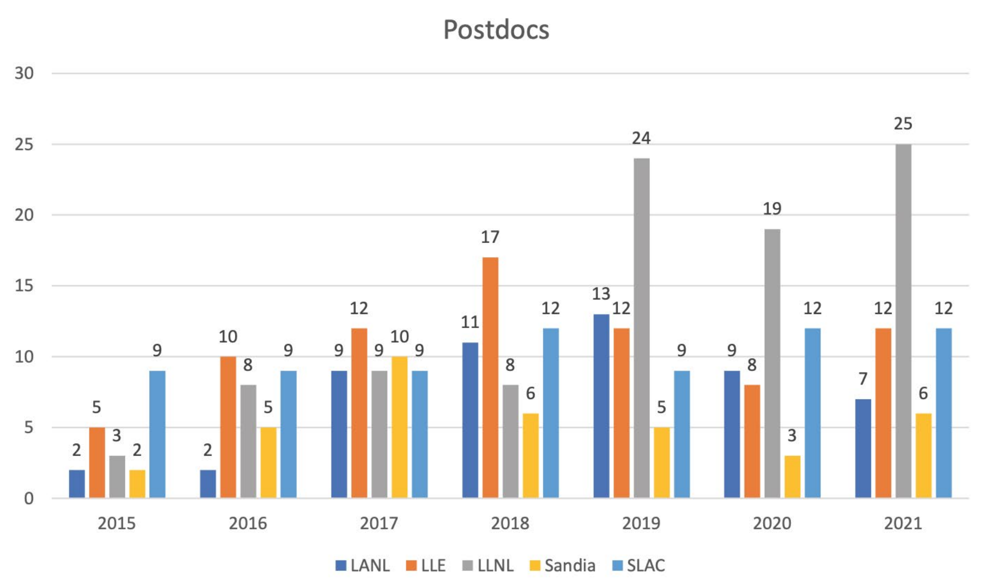

FIGURE 4.3 Numbers of postdoctoral researchers at the National Nuclear Security Administration/Department of Energy high energy density facilities—Los Alamos National Laboratory (LANL), Laboratory for Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (Sandia), and Stanford Linear Accelerator Center (SLAC). The SLAC and LLE values are good, and there is a need to increase the numbers at LANL and Sandia. More user access to the other national facilities would greatly assist LANL in attracting postdoctoral researchers.
SOURCE: Data from LANL, LLE, LLNL, Sandia, and SLAC.

National laboratories are also instrumental in building and enabling academic collaborations. While the NNSA has Stockpile Stewardship Alliances Programs (SSAP), they are not sufficient to grow the HED science workforce, and laboratories have created their own academic collaboration programs to support graduate students in residence at the laboratories.

At SNL, the Z Fundamental Science Program provides access to the Z pulsed-power facility for academic users. Also, the Sandia Academic Alliances program offers funding opportunities with a select set of universities, and several summer internship programs provide relatively easy entry points for students and mentors. LLNL has its own HED science center dedicated to outreach and building collaborations with academia, as well as an Academic Collaboration Team University Program (ACT-UP) to support graduate students and faculty in research areas including HED science. LANL has an extensive summer internship program that introduces students to HED science. All three national laboratories have close collaborations with several of NNSA's Academic Centers of Excellence,[1] and laboratory scientists contribute to developing HED curricula and teach at summer schools.

[1] These include the Wootton Center for Astrophysical Plasma Properties, Center for Matters under Extreme Pressure, Chicago/DOE Alliance Center, Center Laboratory Astrophysics, and others.

While some of these programs are sanctioned and/or supported by NNSA or laboratory management, many efforts amount to volunteer efforts by laboratory scientists. Coupled with intense programmatic demands and significant barriers to collaboration, this lack of formal support or recognition can lead to burnout and attrition of the most energetic and dedicated scientists, especially at early-career stages and among staff reflecting diversity—both characteristics are in high demand.

BOX 4.4
Students Learn the Value of Team Science at National Laboratories

The National Nuclear Security Administration (NNSA) national laboratories have summer or residency programs that allow students to experience the value of teamwork, which is essential to the high energy density (HED) science ecosystem. At mid-scale facilities, such as Lawrence Livermore National Laboratory's (LLNL's) Jupiter Laser Facility (JLF), groups of students can join teams of more experienced scientists and researchers to explore HED science experiments (see Figure 4.4.1). They are enthusiastic about these interactions and experiments, and many of them stay in the field.

"I'm really excited to see whether these will lead to new experiments in the future," said a Rice University senior physics and math major. "I know one of the goals is to find things that are interesting, but there may not be time to look fully into now. That's the nice thing about science. We're always opening doors for ourselves for the future."

"The JLF is the place to learn what high-intensity lasers do to matter," said an applied physics grad student from the university of Michigan. "There's not a whole lot of other places that can study that," he said. "This laser is definitely one to use for HED science."

"It brings people from all different schools, from whatever research they're doing, in here to do something totally different," said a Princeton University graduate student. "Every day, we have a plan of what's going to happen. But then the first shot happens, and everything is totally different than we thought, so we change our plans."

Student mentors at national laboratories see enormous value in such interactions, because students represent the future for HED science. "It's a real pleasure to try to have an impact on younger scientists' careers, because I was in their shoes once," says a LLNL staff scientist. "Having them get as much hands-on experience as possible, tweaking things, understanding the setup, is important for them because they have to learn."

FIGURE 4.4.1 Summer students working at Lawrence Livermore National Laboratory's Jupiter Laser Facility, summer 2019.
SOURCE: Adapted from Lawrence Livermore National Laboratory, 2018, "Summer Scholars Learn Value of Team Science," https://www.llnl.gov/news/summer-scholars-learn-value-team-science.

Retention and Recruitment of the High Energy Density Science Workforce at NNSA Laboratories

In a competitive, post-pandemic work environment, the HED science workforce at NNSA laboratories is at risk of facing severe shortages due to attrition and difficulties in hiring (see also Box 4.5).

While some departures can be attributed to retirement, most of the attrition is with mid-career employees (5-7 years) who are leaving the national laboratories to pursue other careers. These include positions in industry, startups (including emerging fusion energy startups), or even at institutions abroad.

BOX 4.5
People Matter

At its best, science is a collective endeavor, committed to fair and rigorous evaluation of ideas from any quarter, and welcoming of thoughtful criticism. At their best, scientists strive to extend that openness to interpersonal interactions, recognizing that their colleagues have unique experiences, and welcoming every new person into a supportive, vibrant, research culture.

In many science, technology, engineering, and mathematics (STEM) fields, women and people of color are severely underrepresented and may feel isolated or even alienated in their work environments. The extra effort required to navigate uncomfortable environments is often exacerbated by implicit expectations that demographic minorities be diligent collaborators, mentors, and committee members, despite not being recognized as often as scientific leaders. For example, in the American Physical Society's Division of Plasma Physics, women regularly represent about 10 percent of the total membership, yet they make up 20 to 50 percent of many service committees and receive only about 5 percent of the prestigious awards and fellowships.

Women and minorities populations also often lack representation outside of their workplace where decisions regarding important issues—ranging from privacy to reproductive rights—too often circumvent their input and interests. In this environment, co-workers' ability to recognize situations in which a colleague is having trouble—and their willingness to take action—are critical to building a successful research environment (see Boxes 4.2 and 4.3). Institutional processes and courageous leadership are needed to enhance cultural standards that contribute to healthy work environments. More than ever, students and early-career scientists, engineers, and technical staff are attuned to these matters, with both recruitment and retention of top talent responsive to and benefitting from an environment that actively promotes diversity, equity, inclusion, and accessibility.

Historically, the United States has benefitted enormously from open and rigorous scientific dialogue. Freedom of speech, politics, and religion have been critical hallmarks of societies in which science, engineering, and technology have thrived. In an increasingly competitive environment, actions reflecting the importance of gender equity, social justice, human rights, and reproductive rights are fundamental to ensuring that talented people from diverse backgrounds can fully contribute to scientific and technological advances that benefit all of society.

This is a complex problem, with some aspects being specific to each NNSA/DOE laboratory. However, one of the key remedies recognized both within the national laboratories and across academia is that enhanced opportunities for collaboration with the broader scientific community lead to considerable opportunities for recruitment and retention. Better yet, when these collaborations include top-quality students and postdoctoral researchers, the win-win result is that the best science is accomplished, and the top caliber of researchers is attracted to and then retained within the laboratory system.

Role of Facilities and the Workforce

World-class facilities (as highlighted in Box 4.6), capabilities, and staff serve as attractors for the best and brightest scientific talent across disciplines. While investments in facilities, capabilities, and programs are mandatory, these need not be at the expense of investments in the workforce. Developments need to proceed at the fastest possible pace and be augmented by investments across the community to maintain and develop expertise in laser-based (including OMEGA EP-OPAL, ZEUS, NIF, and more), and

pulsed-power (Z and others) facilities as well as in the development of high repetition-rate diagnostics, target design and fabrication, and real-time data analytics and associated capabilities in theory, modeling, and simulation.

While many of these areas have wide applicability to the whole of HED science, drivers for HED experiments are specific to a particular technology. Compared to lasers, pulsed power has a relatively small number of university-scale facilities suitable for training new experts in operation and design; and no mid-scale facility that can serve as a training ground for Z, the way that LLE's Omega laser serves as a training ground and steppingstone for the larger NIF. Growth of the community's workforce is essential to underpinning today's remarkable facility capabilities—it is people who innovate and ensure that full value is extracted from facilities.

Finding: Significant barriers exist for broad collaborations and academic development in fundamental research, partly due to restrictions imposed by research in classified domains, thereby inhibiting recruitment and retention, as well as more rapid progress in research.

Conclusion: This is an opportune time for national laboratories to increase collaboration on HED science, by being more accessible and open in sharing results and data with academia, international collaborators, and those in the private sector.

Finding: Technical staff at NNSA laboratories and experimental facilities have developed a unique set of skills that are learned "on the job," including diagnostic techniques, experimental setups, and detectors specific to the needs of HED science.

Conclusion: Training and retention of talented technical staff at NNSA laboratories and experimental facilities are crucial to HED science and the NNSA mission.

Conclusion: Formal programs that enable and reward collaborations, outreach, and mentorship significantly increase the vitality of the workforce, improving both recruitment and retention of highly trained specialists.

Recommendation: The NNSA should provide explicit support and recognition for national laboratory scientists to increase collaborations, mentorship, and outreach with the fundamental research community, in order to build public excitement and the future workforce. Examples include joint appointments or sabbatical opportunities and travel/lectureship programs that partner with minority-serving institutions and the public at large.

Recommendation: The NNSA should periodically assess and, where possible, reduce barriers to university collaborations—for example, by formally recognizing the importance of, and therefore supporting and rewarding, laboratory staff engaged in effective collaborations.

Recommendation: NNSA laboratories should enforce concrete policies for accountability around intolerable, unacceptable behaviors.

Recommendation: In addition to training Ph.D. scientists, NNSA laboratories should invest in educational (apprenticeship) programs at institutions for training of technicians and technical staff at the bachelor's or master's level, doing so in line with the laboratories' diversity, equity, inclusion, and accessibility goals.

Recommendation: NNSA national laboratories should promote collaborations with academia by sharing data related to unclassified research (in consistent data format) and providing open/educational versions of their computational codes.

BOX 4.6
Access to Premier U.S. Facilities in High Energy Density Science Is Essential for the Workforce

Flagship high energy density (HED) science facilities (e.g., the National Ignition Facility, Z Pulsed Power Facility, and Omega Laser Facility) hosted by national laboratories or universities serve as attractors for talent and make it easier to maintain vibrant HED science programs (see Appendix C). These infrastructures are under high demand and therefore cannot provide hands-on training for the entire workforce of the future; they are also limited in number. Increased access to mid-scale facilities, where students and scientists from any institution can learn to set up experiments, and develop scientific ideas and platforms, are key to the future of the field.

Motivated by the success of LaserNetUS (see Figure 4.6.1; a network of high-power laser facilities created in 2018 and operating effectively as a user facility and supported by the Department of Energy's Office of Fusion Energy Sciences), several communities are forming facility networks to allow equitable access to unique national resources. The vision of LaserNetUS is to advance the frontiers of ultra-intense laser science, and the group's mission is to sustain U.S. scientific competitiveness in HED and high-field optical science by advancing the frontiers of laser-science research, providing students and scientists with broad access to unique facilities and enabling technologies, and fostering collaboration among researchers and networks from around the world.

The broad range of capabilities of the various facilities and its open mission put LaserNetUS, and now ZNetUS, in an excellent position to advance science, technology, and the workforce for HED science. The 10 LaserNetUS facilities (see Figure 4.6.1) have different but overlapping and complementary capabilities, both in laser systems and experimental facilities and apparatus. LaserNetUS is a new entity, and its continued growth benefits HED science and the workforce. Indeed, it has already had a large impact on the HED science community, supporting more than 60 experiments involving more than 400 users, including over 100 students. The network includes simulation and diagnostic coordination programs, which are both essential to the success of any HED experiment.

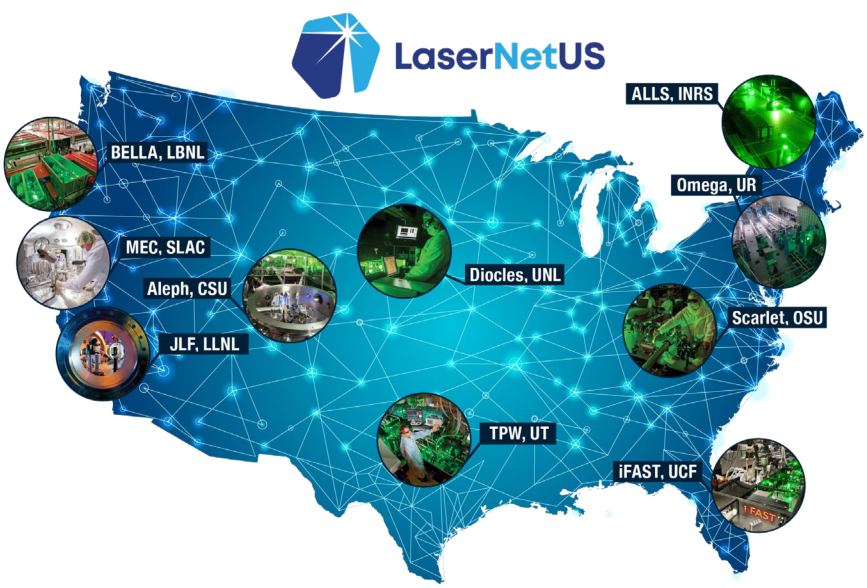

FIGURE 4.6.1 Facilities of LaserNetUS, a network of 10 high-power laser facilities enabling access to high energy density science research to researchers from any institution.

SOURCE: Courtesy of LaserNetUS—a U.S. Department of Energy Office of Science, Office of Fusion Energy Sciences Initiative.

ROLE OF INDUSTRY

With each new generation of HED science facility, new and innovative technologies need to be developed to fully explore new regimes of matter. Whether it is a new type of computing architecture, large diameters of laser glass, or cameras that can record faster time scales and smaller resolutions, experimental facilities not only provide a platform, but a rich new set of technologies that have impact far outside HED science. Advances in computational capabilities have likewise depended on close collaboration between industry and national laboratories.

Since the first experimental facilities were developed, a long-standing history of industry supporting HED science facilities has existed. In some cases, the facilities themselves would not be able to exist without extensive industrial collaboration. Additionally, the new technologies and science applications in HED-relevant areas have significant industrial applications, including in fusion energy, secondary radiation sources, and compact accelerators.

NNSA HED experimental facilities engage with industry in a wide variety of ways. For instance, during the development of the NIF and Omega laser facilities, new large-aperture glasses and crystals with extremely high damage-threshold optical coatings were developed. Schott Glass Technologies and Hoya Corporation collaborated to develop the new technologies with LLNL over a decade-long timeframe, allowing the facility to successfully achieve its ambitious design specifications.

The NNSA Exascale system El Capitan, developed by Cray Supercomputers, required the development of a computational technology that is 4 times as energy efficient yet 10 times more powerful as the current Sierra supercomputer.

The large scale of HED campaigns has also prompted the formation of several startups to develop critical diagnostics required for experiments. For instance, Kentech Technologies, Photek, and Sydor Instruments have developed ultrafast X-ray spectroscopic capabilities to enable new measurements of HED interactions. This symbiotic relationship between HED science research and industry has far-reaching implications. In one famous example, mirror technology used in HED experiments led to the formation of a virtual national laboratory that ultimately led to the successful development of extreme ultraviolet (EUV) lithography, the current technology used for making computer chips (see Box 2.3).

Despite this long and successful history, retirements and the lack of major new facilities over the past decade have reduced the ability for industry to plan strategically. There are growing concerns that upcoming challenges requiring industry support will not be met, based on current planning.

For instance, while the majority of NNSA facilities operate in a single-shot mode, new facilities are anticipated to have higher repetition rate, with orders of magnitude higher data acquisition. This will require new technology, both to generate the HED sources, and for new detection and data analysis techniques.

Machine learning is an area in which U.S. industry leads, but there are currently substantial barriers to investing in HED science research. Industry often invests in areas where they see clear, obvious, economic pull. Whereas funding mechanisms such as help from the Small Business Innovation Research program to support new startups, the rapid pace of technology development combined with the long timelines imposed by the SBIR process means that by the time a proposal is approved, newer technology may become available, and the impact of the technology diminished.

For larger campaigns such as ICF, it is clear that target technology can have a sizable impact. However, there is a limited effort to push target development forward, and it is clear that more complex technology will be needed in the future. A consensus is that resource commitments being made in this direction are too few to sustain HED work into the future.

There is also a role that industry plays with regard to the workforce. Students and postdoctoral researchers working in HED science are often unaware of the opportunities that exist outside the NNSA

facilities and academia. As opposed to the limited number of locations of the latter institutions, industry provides far more flexibility when it comes to location, which can help improve participation. Additionally, greater industrial involvement offers the opportunity to expand the HED science workforce. More visibility of industrial opportunities related to HED science can broaden the community, as a wider range of career options can improve recruitment and retention.

More recently, there has also been a rapid increase in the number of companies that perform work related to HED science, specifically in inertial fusion energy (IFE). Given the long-standing expertise in HED science, combined with the historic success of industrial collaboration, there is an opportunity for the NNSA to develop partnerships with these companies to strengthen and broaden the HED science workforce. Doing so will also develop new technologies that are mutually beneficial for both fundamental-science and industrial applications. Without greater partnership, leadership, and strategic planning with industry, the NNSA is risking increased competition for the top-caliber workforce and decreased capability to meet the science technology needs for the future.

Recommendation: The NNSA should collaboratively develop industry-relevant technical roadmaps for critical capabilities in computation, diagnostics, and targets and provide more—and more frequent—funding opportunities for industry to provide these capabilities.

5

International Aspects of High Energy Density Science

OVERVIEW

This chapter broadly reviews the international high energy density (HED) science landscape, including brief words on collaborations versus competition, the international HED science workforce, and sensitive information.

As a disclaimer, the committee did the best it could in trying to marshal evidence about relative strength of science in different countries. The committee was also unable to obtain reliable information on programs in China and Russia, with various claims lacking independent validation. Level of investment, availability of facilities and the like serve, at best, as proxies, and the evidence is mainly anecdotal. Additionally, the committee was not aware of recent developments allowing it to assess theory, modeling, and simulation capabilities internationally.

INTERNATIONAL HIGH ENERGY DENSITY SCIENCE LANDSCAPE

Traditional HED science with high-energy lasers and pulsed-power Z-pinches is still led by the United States. The National Ignition Facility at Lawrence Livermore National Laboratory remains the leader in laser energy at 1.8 MJ, and Sandia National Laboratories' Z-pinch is the most powerful, operating at currents of 26 MA.

There is only one similar laser facility, the Laser Megajoule (LMJ) facility at the French Alternative Energies and Atomic Energy Commission (CEA). It is currently ramping up to reach a maximum energy of 1.3 MJ by 2025. The LMJ is operational with the current research primarily devoted to France's nuclear-weapon Stockpile Stewardship Program (see Box 4.1), although like NIF, there is some limited academic access through an open call program. LMJ and NIF have active and fruitful collaborations and exchanges on facility, diagnostics, and ICF experiments.

The highest power Z-pinch outside the United States operates at a current of 8 MA and is located at the Julong-1 facilities at the China Academy of Engineering Physics (CAEP).

Although HED science has been traditionally carried out at large experimental facilities with either high-energy lasers or with pulsed power Z-pinches, the growth in Petawatt scale lasers is changing the outlook of HED science. In 2021, using the CoReLS laser, at the Center for Relativistic Laser Science in Gwangju in the Republic of Korea, the highest laser intensity to date was measured at 1.4×10^{23} W/cm^2. Light pressure is given by the intensity divided by the speed of light. This intensity then gives a pressure of over 10^{20} Pa, which is more than 9 orders of magnitude larger than the pressure threshold of 100 GPa for HED science.

With these extreme light pressures, new directions are being discovered for HED science in areas such as new matter and materials created by laser-induced, high-pressure extreme states; shock physics in plasmas; particle acceleration; laboratory astrophysics with giant magnetic fields; and vacuum quantum optics. These high laser intensities can be reached at a greatly reduced energy with ultrafast lasers, which use lower-cost facilities than the traditional high-energy laser ICF facilities (see also Box 5.1).

As noted in the 2018 National Academies of Sciences, Engineering, and Medicine report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*,[1] Asia and Europe now lead in this field, even though the first petawatt lasers were developed in the United States. Figure 5.1 shows the global distribution of high-intensity lasers. Not only does Europe have far more high-intensity lasers than North America, the most powerful lasers are in Europe and Asia. The Korean laser has a power of 4 PW, while in Europe the Extreme Light Infrastructure Nuclear Physics facility demonstrated laser powers of 10 PW in 2020. The United States does not have any lasers at the 10 PW power level, while China is now developing a 100 PW laser system.

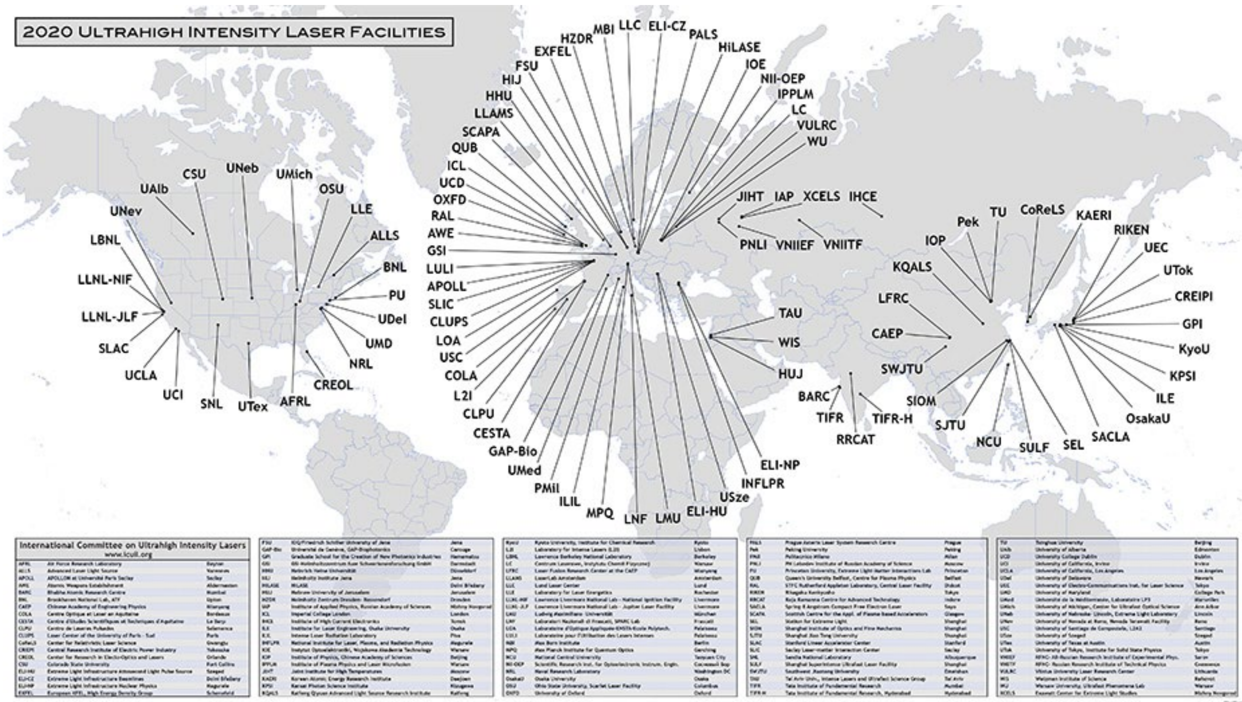

FIGURE 5.1 Ultrahigh-intensity laser facilities around the world, showing rapid growth in Europe and Asia.

SOURCE: Courtesy of the International Committee on Ultra-High Intensity Lasers, https://www.icuil.org/index.php.

Materials science under extreme pressure can now also be studied at small facilities using diamond-anvil technology. The largest effort in this domain is being carried out at a new research center in China, HPSTAR: Center for High Pressure Science and Technology Advanced Research (see Box 5.2). Forefront HED research is more international than ever, overall (see Figure 5.2).

Finding: The current and planned high-intensity lasers in Europe and Asia far exceed the power of those in the United States.

Conclusion: The dominant position that the United States has held in HED science is being eroded by the global growth in both high-intensity laser facilities and high-pressure research facilities outside the United States.

[1] National Academies of Sciences, Engineering, and Medicine, 2018, *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, Washington, DC: The National Academies Press, https://doi.org/10.17226/24939.

Recommendation: To strengthen its global leadership in high energy density science and address future national needs, the NNSA should increase the promotion of forefront technology development, and in particular take the necessary steps to achieve ultra-high power laser capabilities on par with what is being developed around the world.

BOX 5.1
Harnessing Laser-Plasma Accelerators for Novel Light Sources at International Facilities

Large-scale light sources used for investigating high energy density(HED) matter, such as synchrotrons and X-ray-free electron lasers (XFELs), rely on conventional accelerator technology. While radio frequency (RF) accelerators present several advantages, including robustness, reliability, and a high repetition rate, the accelerating gradient is limited to about 100 MV/m, due to electrical breakdown in the cavities. Plasma-based acceleration, proposed four decades ago, does not have this limitation and can sustain accelerating gradients 1,000 times higher, making the machines much more compact, cost-effective, and flexible if they are to be coupled to larger-scale lasers as diagnostic probes for HED science experiments.

The international research community has been very active in this area, and most advances and breakthroughs are now made at facilities and institutions outside the United States.

Among light sources based on laser-plasma accelerators, the holy grail would be to someday power an XFEL using this technology. This demonstration was achieved for the first time in July 2021 by researchers at the Shanghai Institute of Optics of Fine Mechanics in China, or "SIOM". While XFELs based on RF-technology are kilometers in length, the Shanghai setup was only 12 m long.

The complex laser-plasma interaction physics is not yet fully mastered to make this type of machine as reliable as a conventional XFEL, but there are several large-scale initiatives to overcome these difficulties. EuPRAXIA is a $500 million-funded trans-European facility aiming to produce beams superior to those available today. Research groups in Europe, such as in DESY in Germany or Rutherford Appleton Laboratory in the United Kingdom, have dedicated research groups and infrastructures to tackle these issues. The laser-based accelerator LUX at DESY recently demonstrated that it can run 24 hours while firing 1 shot per second, and it uses Bayesian optimization and machine learning to stabilize the accelerator. (See Figure 5.1.1)

Except for projects at Lawrence Berkeley National Laboratory, the United States does not have a dedicated effort in this area and could risk missing on key advances beneficial to the field of HED science.

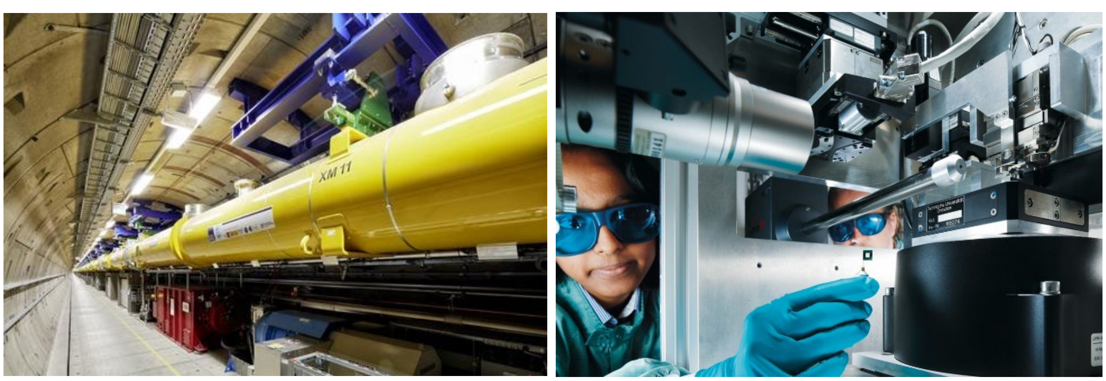

FIGURE 5.1.1 European XFEL accelerator tunnel with yellow superconducting accelerator modules (*left*), a measuring station at PETRA III (*right*).
SOURCE: European XFEL/Heiner Müller-Elsner (*left*), © DESY / Heiner Müller-Elsner (*right*).

BOX 5.2
HPSTAR: Center for High Pressure Science and Technology Advanced Research
Beijing, Changchun, and Shanghai, China

FIGURE 5.2.1 HPSTAR Beijing.
SOURCE: H. Mao, 2016, "High Pressure Presses Ahead," *Nature Materials* 15(7):694-695, http://dx.doi.org/10.1038/nmat4642.

The stated goal of HPSTAR (Center for High Pressure Science and Technology Advanced Research) is to promote world-class research in high-pressure science and technology. Established in 2013 under the directorship of Ho-Kwang Mao, it currently has three campuses: Beijing, including experimental laboratories and the main administrative offices; Shanghai, the original site housing the main experimental laboratories (located next to the Shanghai Synchrotron Radiation Facility); and Changchun, which also has experimental laboratories. Much of the research involves applications of diamond-anvil cells and first-principles theory to topics in physics, chemistry, materials science, and Earth and planetary sciences.

The center is projected by 2023 to have a full-time scientific staff of 90, supported by 600 additional members, including graduate students, postdoctoral researchers, visiting scientists, engineers, and administrative staff, with funding coming from the Ministry of Finance of the People's Republic of China.[a] Although most are Chinese, the staff has been recruited internationally, and includes members and visitors from Canada, Germany, Japan, the United Kingdom, and the United States.

Among the largest research institutes in high energy density science in the world, HPSTAR is reportedly modeled on the Carnegie Institution for Science (U.S.) and Max-Planck Institutes (Germany), and it is committed to becoming a global center in high-pressure science and technology. Less than 8 years after its inception, *Nature Index* shows an annual count of 54 HPSTAR publications,[b] with publication shares rising from 7.4 to 17.6 between 2016 and 2021. For comparison, the 120-year-old Carnegie Institution for Science's current annual publication count is 119 across all disciplines (publication share of 26.3).

[a] See http://hpstar.ac.cn.
[b] See https://www.nature.com/nature-index/institution-outputs/china/center-for-high-pressure-science-and-technology-advanced-research-hpstar/5243e7f6140ba09f4a000008.

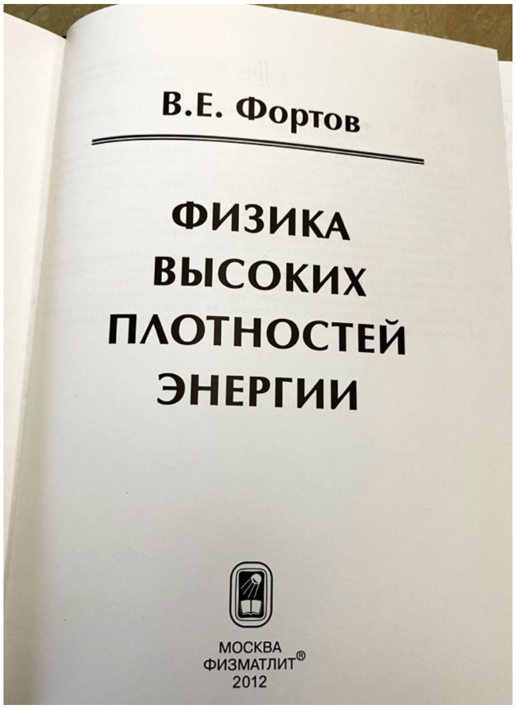

FIGURE 5.2 High energy density science engages a broad international scientific community. This point is illustrated by the 2012 textbook of V.E. Fortov, former President of the Russian Academy of Sciences. SOURCE: Courtesy of R. Jeanloz.

INTERNATIONAL COLLABORATIONS

International collaborations enhance the utilization of HED facilities by offering access to the most diverse and capable workforce. HED facilities are currently mostly utilized by local-national scientists, followed by scientists from the same region of the world.

The main international users of U.S. HED facilities come from Europe; and, likewise, U.S. HED scientists utilize European facilities more than the Asian facilities. Since the highest-intensity laser facility is in Korea, access to that facility should be highly sought, but there does not yet seem to be a good program to bring U.S. researchers to that facility, even though it is open to international scientists and is used by the Europeans.

With the formation of LaserNetUS (see Box 4.6), there is now a channel for international collaborations between laser scientists from Europe, Asia, and North America, so this may improve the level of collaboration with U.S. scientists. Europe and Asia have both established continental networks, LaserLab Europe and the Asian Intense Laser Network (AILN), and already have ongoing collaborations between these two networks.

New international agreements for HED science research, such as the program between U.S. DOE and Japan MEXT in 2019, would aid these collaborations.

International collaborations could also be facilitated through better remote access to the facilities (see Box 5.3). This would help remove the time and expense barriers imposed by travel. Remote access has been increased, especially at the Laboratory for Laser Energetics and other facilities, because of COVID-19 restrictions, and more work needs to be done to improve both the experimental control and the data acquisition for international and domestic remote users at all HED facilities. In principle, remote access provides a means of controlling access in ways that enhance information security as well as scientific productivity.

Finding: International collaborations strengthen collaborations within the HED science workforce and enhance the utilization of HED facilities leading to breakthroughs.

Conclusion: Increasing remote access to HED facilities would greatly enhance their utilization by both domestic and international users.

Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should promote international collaborations and increase remote access to those facilities.

BOX 5.3
Remote Access: A Boon for *All* Countries

The most prominent high energy density (HED) science facilities, such as National Ignition Facility at Lawrence Livermore National Laboratory, Z Pulsed Power Machine at Sandia National Laboratories, and Omega at the University of Rochester, are large and expensive infrastructures. Constructing and operating similar facilities are beyond the budget capabilities of most nations; access is severely limited even within the United States.

However, the need to operate such large infrastructures as remote access facilities has been greatly accelerated by the COVID-19 pandemic. That experience could be a boon to accessibility for collaborating students and researchers from institutions disconnected for historical reasons, whether from within the United States (e.g., Minority Serving Institutions, Historically Black Colleges and Universities) or from partner countries.

The concept of remote access is not unique to HED science facilities. An excellent example of exploiting this mode of operation is provided by advanced light sources, such as synchrotrons and X-ray-free-electron lasers. These facilities have proved to be transformational in a myriad of disciplines, including biology, chemistry, cultural history, geoscience, materials science, medicine, paleontology, and physics.

Globally, there are just over 50 advanced light sources in operation, and the COVID-19 pandemic forced many to make remote access available to users. One in particular, SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East), well-known for bridging political differences across the Middle East, shifted much of its operations to remote access. As such, researchers who are otherwise unable to work at advanced light sources costing several hundred million dollars, can still have remote access to state-of-the-art facilities.

To maximally exploit remote access, it is important for users to first spend time at the facility in order to gain hands-on experience with the beamline equipment and measurement techniques, understand and gain access to the latest data analysis tools, and spend time working with the onsite beamline scientists.

Indeed, there are programs to facilitate such efforts. An excellent example is *LAAAMP* (Lightsources for Africa, the Americas, Asia, Middle East and Pacific, https://laaamp.iucr.org), a joint program of the International Union of Pure and Applied Physics, International Union of Crystallography, and the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy.

A main goal of *LAAAMP* is to enhance the utilization of advanced light sources in Africa, Mexico, the Caribbean, Central and Southeast Asia, the Middle East, and the Pacific Islands. As such, one of *LAAAMP*'s programs sends faculty and graduate student teams to facilities for 2 months of initial training, followed by another 2 months the following year. Figure 5.3.1 shows one such visit to Thailand's Synchrotron Light Research Institute by a faculty-student team from Botswana International University of Science and Technology. After such visits, *LAAAMP* provides funding to assist researchers with sending experimental samples for further data acquisition.

This utilization of advanced light sources via remote access can serve as a model for far more researchers gaining access to large HED science facilities than has been historically feasible. The objective is to advance the quality of science and training of researchers by broadening the network of those having access to the best facilities, whether from across the United States or internationally.

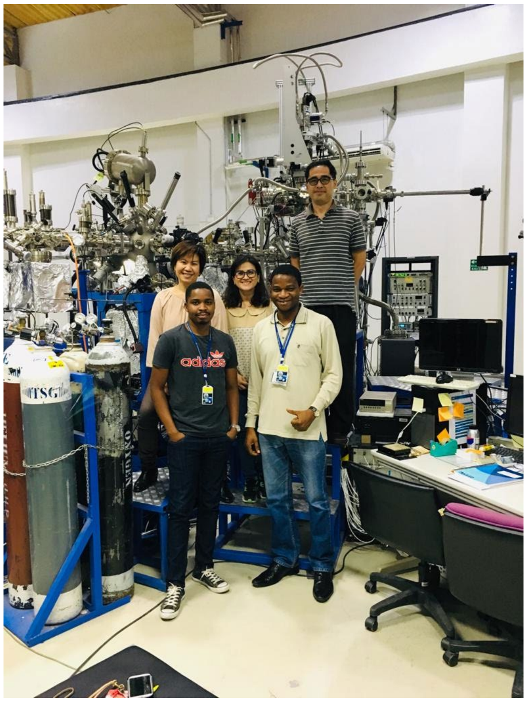

FIGURE 5.3.1 Oluseyi Philip Oladijo (front right) and graduate student (front left) from Botswana International University of Science and Technology on a 2-month visit during 2018 to the Synchrotron Light Research Institute in Thailand.
SOURCE: Courtesy of P. Oladijo.

INTERNATIONAL WORKFORCE

The United States will need to find ways to attract domestic students and retain international students in relevant domains of science and technology, and to work out solutions allowing those students trained in the United States to remain in the country.

Because much of HED science carried out at large facilities is tied to national needs in the United States as in other countries (e.g., Box 4.1), the workforces at these national facilities come mainly from the home country. The workforce at China's ICF facility is 100 percent Chinese, for example. To train this workforce, China has graduate level programs in the relevant areas of science and engineering.

Graduate programs within the United States have benefitted from large enrollments of international students. In physics, chemistry, and material sciences—areas relevant for HED science—a significant portion of the students receiving Ph.D.s is international: 35 percent in physics, 39 percent in chemistry, and 50 percent in materials science. This level of international student participation also occurs in the university graduate programs held in conjunction with the HED facilities at Stanford University and University of Rochester.

The United States has historically benefited greatly from the immigration of scientists from around the globe. Their skills and perspectives have helped make the United States a historical leader in science and engineering, HED science included. The international character of the U.S. workforce is at risk for a number of reasons, however. First, the number of international graduate students is declining because these students are now experiencing constraints on visas that make it difficult for them to study or work in the United States. Second, competing opportunities in their home country are increasingly attractive.

The rapid growth of HED science as a field having national impact has motivated major investments by several countries, some of which already exceed U.S. capabilities (e.g., in high-intensity

lasers). In addition, multiple facilities are planned that significantly exceed U.S. capabilities, in both lasers and pulsed power. This could have a major effect on the U.S. ability to recruit the expert, world-leading workforce needed to maintain a vibrant research capability.

HED science is a collaborative field in nature and maintaining strong national and international collaborations facilitates retaining and recruiting a global workforce. The growth of HED science offers opportunities for increased collaborations with diverse fields, but it requires a vastly larger network of partnerships and collaborations, both domestically and internationally, as no one institution can hope to address all the scientific areas of such a vibrant field. Thus, the HED science community should be supported in its active efforts to strengthen and grow partnerships between NNSA laboratories, DOE's Office of Science laboratories, universities, and industry.

> Finding: The United States offers many advantages in facilities and cutting-edge HED science research, which makes it a desired location for pursuing postdoctoral research and a career in HED science, although this might change investments by several countries match or even exceed this posture.
>
> *Conclusion: No one institution can hope to address all of the scientific areas of such a vibrant field. The future of HED science is about partnerships and collaborations, including with international institutions.*

INTERNATIONAL SCHOLARS AND THE IMPORTANCE OF PROTECTING SENSITIVE INFORMATION

International scholars have been major contributors to the research strength of the United States for over a century. As U.S. universities are the envy of the world, international researchers have played a major role in creating that strength. In projects of national security import, such as the Manhattan Project, international contributors from Fermi to Bohr and Bethe played major roles.

The United States has provided, and continues to provide, a welcoming culture for international students and mature researchers—researchers who are committed to pursuing their research in an environment where research integrity is highly valued. These contributors, many of whom have chosen to make the United States home by becoming U.S. citizens, are an integral part of our research strength today. Were the United States to be seen as an unattractive research destination for international researchers, the United States would incur a growing risk of mediocrity and decline.

There are three key reasons why it is essential that the U.S. HED science community strike the proper balance in welcoming international scholars and protecting sensitive information.

- **Quality of science.** The quality of science in all domains—fundamental, applied, and in service to the nation—is enhanced by broad collaborations because new ideas and creative breakthroughs come from all directions. Thus, wherever possible, encouraging collaborations, including among international researchers, is critical to the health of U.S. science and technology.
- **Workforce.** Prior to 2020, approximately 80 percent of international students who studied in the United States have wanted to remain here. These students have, in many cases, become strong contributors to the science, technology, and engineering advances in the United States. Continuing to attract the best minds from the international community is important for continuing advances in science.
- **Maintaining and advancing international understanding and collaborations.** Just as the United States maintains informal diplomatic discussions and military-to-military engagements,

scientist-to-scientist engagements offer a mechanism for building international understanding, confidence, and insight.

The HED science community is competing for the best minds on a global scale. The good news is that the combination of research environments available in the United States and the structure of U.S. society have been attractive to many international researchers. As other nations are ramping up their research efforts, they too are competing for talent, at times in ways that are antithetical to the norms that characterize research in the United States.

Although the present report is focused on basic research, the committee acknowledges that HED science overlaps with topics having military applications or other sensitivities. Therefore, the committee briefly addresses the interface between sensitive and open research, so as to emphasize that the relationship between the two must be judiciously managed as progress is made in fields related to HED science. In particular, either ignoring the topic or overly constraining research activities in HED can cause significant harm to scientific progress or to national and international security.

As with all other areas of open scientific research, information needs to be properly managed so as to enhance collaborations and advancement of the science in a manner that is mutually reinforcing, sustainable for all involved, and in line with existing laws and regulations (e.g., the National Science Foundation's efforts,[2] and its 2019 Fundamental Research Security report).[3]

This means that procedures must be in place for making experimental data and results of theory or simulations suitably available among researchers as well as the public at large, and that these procedures are understood and practiced by all participants. Investigators, their institutions, and the user facilities all have responsibilities for ensuring proper access to research results, and any restrictions or special access (e.g., due to licensing agreements) need to be documented, justified, and applied in a transparent manner.

More complex is the issue of export control and related regulations that apply to dual-use research, including the International Traffic in Arms Regulations[4] (ITAR) and Export Administration Regulations[5] (EAR) that are largely intended to counter the proliferation of military technologies.[6] Hardware, software, and either general concepts or the specific results of a study can all be subject to restrictions, and the limitations may vary depending on an individual's nationality. In other words, a student from one country may be allowed to use a certain computer code, whereas a student of different nationality might not have access to that software, even if working in the same research group. Specific examples include hydrodynamic simulations used for designing HED experiments, which may have restricted access.

It is up to investigators and their institutions to be familiar with these regulations, not only so as to comply with existing laws but also to avoid overly restrictive constraints being placed on scientific research or collaborations. The concern is that inattention by one researcher or institution could prompt the imposition of onerous new restrictions affecting the entire research community—restrictions that would not have been necessary had existing regulations been followed.

More serious, and in some ways more straightforward, is the management of classified information. Here the problem is that unclassified experiments, simulations, or theories and models can in principle produce classified results. Perversely, the silence of the classified community in areas that are well understood by the scientific community risks calling undue attention to sensitive areas. Worse, given the international character of HED science, what is considered unclassified can differ from one country to another.

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[2] See https://nsf.gov/od/recr.jsp.

[3] See https://www.nsf.gov/news/special_reports/jasonsecurity/JSR-19-2IFundamentalResearchSecurity_12062019FINAL.pdf.

[4] See https://www.pmddtc.state.gov/ddtc_public.

[5] See https://www.bis.doc.gov/index.php/regulations/export-administration-regulations-ear.

[6] "Dual use" generally refers to research that can have harmful as well as beneficial applications, and in the present context can be taken as referring to research that can be used for military applications or terrorism.

In the mid-1990s, the Secretary of Energy commissioned a fundamental classification review. The report of the DOE Report of the Fundamental Classification Policy Review Group (1997) recognized the problems inherent in the "born classified" concept of the Atomic Energy Act of 1954 and recommended changes to the act. In addition, the review recognized that domains that had become of interest to the wider scientific community could be sensitive or classified. While the sweeping changes recommended by this review committee have not been implemented, in the past few years, there have been changes to the classification guidance for both equation-of-state and opacity that are fostering better exchanges between those working in the classified and unclassified communities.

Recognizing the delicacy of research that lies on the boundaries of classification, the primary mitigation for these difficulties at the present time is for facilities and the funding agencies, and—if possible—the investigators and their institutions, to (1) have safeguards for recognizing when prospective research might generate such sensitive information and (2) establish means of mitigating these circumstances. The committee does not elaborate on the best solutions to these issues, but rather emphasizes the need for addressing them within research programs, institutions, and facilities supporting HED science.

Ensuring the health of the research enterprise while simultaneously protecting sensitive information requires a deft touch that engages the research culture, information systems, and researchers.

Information Processing System Security

The current framework is appropriate. As with all U.S. institutions, both universities and national laboratories are bound by existing laws and regulations. Examples include ITAR and classification rules. These are not unlike regulations such as Health Insurance Portability and Accountability Act and Family Educational Rights and Privacy Act in other domains. Given the dynamic nature of information security in cyber space, one can anticipate evolution in the legal and regulatory domain. Similarly, just as U.S. institutions are assumed compliant today, one can anticipate that they will continue to be compliant under current regulations and laws in the future.

Vetting of Foreign National Researchers

The government, universities, and national laboratories have a shared interest in ensuring research integrity through the values of openness and transparency, accountability and honesty, impartiality and objectivity, respect, freedom of inquiry, reciprocity, and merit-based competition—as outlined in the National Science Foundation "Dear Colleague" letter and the National Science and Technology Council's "Recommended Practices for Strengthening the Security and Integrity of America's Science and Technology Research Enterprise."

While most researchers both in the United States and abroad share these values, not all do. To ensure the integrity of research, it is important to confirm that researchers are not obviously compromised, either through conflict of interest or conflict of commitment. Research institutions are expected to instill the values of research integrity into all researchers, both United States and internationally; specifically, these values need to be defined, communicated, and confirmed in all activities.

In addition, because students and researchers may have been exposed to other value systems, research institutions are expected to exercise due diligence when it comes to the engagement of all researchers. While prudent precautions are necessary, it is also clear that no security measures will guarantee that incidents of concern will not occur; they will. When they do, they must be addressed in balanced ways that forward the simultaneous goals of ensuring the health of the HED science research enterprise and protecting sensitive information.

> Finding: It is critical to protect only the right information in HED science. There is programmatic risk from both under and overly restrictive constraints on research results.

Finding: U.S. government policy embodied in regulatory frameworks is existing and evolving rapidly to address challenges in both the cyber and international research environments.

Conclusion: There is a critical need to provide clear communication about the existing classification boundaries to minimize friction between the classified and unclassified communities and foster communication that is as broad as possible without compromising issues of national security.

Leading Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should (1) broaden its current programs for achieving excellence through diversity, equity, and inclusion while improving workplace climate and (2) develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, such as for collaborators internationally, and with academia and the private sector.

Appendixes

A

Approaches to Inertial Confinement Fusion

LASER INDIRECT DRIVE

The indirect-drive approach to inertial confinement fusion (ICF) uses a complex chain of energy transfers to drive a highly controlled implosion of a cryogenic, spherical capsule containing fusion fuel. At its hottest and most dense state (called stagnation), the fuel reaches pressures approaching 300 Gbar and is confined for a fraction of a nanosecond.

With laser indirect drive (LID), as seen in Figure A.1, lasers are directed onto the inner walls of a cylindrical cavity called a hohlraum, at the center of which sits the spherical, fuel-filled implosion capsule. The hohlraum is made primarily of heavy metals (Au or DU), which efficiently convert the energy of the laser light into X rays. Acting as a X-ray oven, the inner walls of the hohlraum provide a symmetric bath of X-ray radiation that reaches a blackbody temperature up to ~250 eV (for reference, the blackbody temperature at the surface of the sun is ~0.5 eV).

The spherical fusion capsule at the center of the hohlraum consists of a shell (called an ablator) that is made of plastic, beryllium, or diamond that encloses the fusion fuel, which is DT ice and gas. The capsule must be cryogenically cooled before the experiment so that a layer of DT ice forms on its inner surface (providing a fuel layer that can trap the energy from the initial fusion reactions) and to keep the initial pressure low (to make the capsule easier to implode). It must also be extremely symmetric and smooth, since defects in its initial stage will be amplified under compression.

As the X rays from the hohlraum illuminate the capsule, the material at the capsule surface is heated and expands away from the main capsule, or ablates. Since every action has an equal and opposite reaction, the remaining capsule material responds to this ablation by moving inward, imploding the capsule. The laser power is designed to launch a series of exquisitely timed shocks into the capsule, which compress and heat the fuel to fusion-relevant temperatures (>4000 eV).

To reach these temperatures, and to amplify the ~100 million atmospheres (Mbar) of pressure generated via X-ray ablation to obtain the hundreds of billions of atmospheres (Gbar) of pressure needed for ignition, the capsule must be imploded on itself by a factor of ~30 at a very high velocity (~400 km/s). This implosion, which is like compressing a balloon to the size of a BB, must be highly symmetric and controlled to maintain a uniform compression of the increasingly hot and dense fuel.

As the drive pressure reaches its maximum, the very center of the fuel becomes hot enough to produce initial fusion reactions. If the remainder of cooler, dense fuel has enough inertia to hold itself together (confine itself) long enough to trap the energetic fusion reaction products from these initial reactions, it can return their energy to the dense fuel layer as additional heat. If the confinement time is sufficient, this self-heating can increase temperatures to 20,000 eV, exponentially increasing both the participating fuel volume and rate of fusion reactions, leading to an explosive release of energy called ignition.

LID is a complex and challenging effort. The laser energy, which is currently limited to 1.8 MJ, must be delivered with precise timing and spatial control into the cylindrical hohlraum in such a way that the hohlraum X rays produce highly uniform irradiation and well-timed ablative shocks to the spherical capsule. Small imperfections in the target and asymmetries in the X-ray drive can be amplified greatly by the rapid, high convergence ratio implosion and, if not adequately controlled, disrupt the capsule and quench ignition. The first ignition efforts on NIF were hampered by—among others—laser-plasma

interactions in the hohlraum that led to energy losses in the drive (but which were ultimately harnessed to provide symmetry control), engineering features on the capsules (such as the fill tube and thin plastic "tent" that suspended the capsule in the hohlraum), and capsule imperfections (bumps and voids). A decade of extraordinary efforts enabled the inertial fusion community to measure, understand, and mitigate many of these complexities.

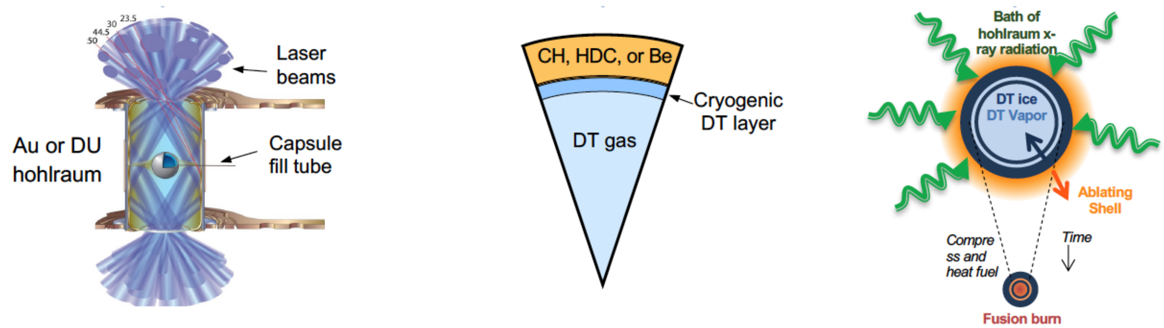

FIGURE A.1 Laser Indirect Drive ICF involves laser beams generating x-rays inside a hohlraum (*left*) to compress a capsule containing DT ice and gas (*center*), the result being compression and heating of the capsule to conditions of thermonuclear fusion (*right*).
SOURCE: Courtesy of Lawrence Livermore National Laboratory.

Outlook

The earliest LID designs fielded on NIF were part of the National Ignition Campaign (NIC), which ended in 2012. These experiments led to the discovery that the laser plasma instability could be used to control beam energy deposition on the hohlraum, which provided a way to control the large-scale symmetry of the implosions. However, NIC implosions had time-dependent drive asymmetries and perturbations seeded by capsule features and imperfections that precluded the control needed for robust performance.

The High-Foot campaign, which followed NIC, used higher powers in the early part of the laser pulse to reduce instability growth in the ablation front. This change led to higher implosion velocities and yields (around 25 kJ of fusion energy, compared to ~5 kJ for NIC), but at the cost of reduced compression. The reduced compression helped enable high-resolution imaging of the implosions that revealed the importance of the capsule perturbations, such as tent scars.

Next, designs using high density carbon (HDC/diamond) ablators and shorter pulses were tested. The hohlraum gas fill was lower density than for NIC, which reduced Stimulated Raman Scattering (SRS) and increased the efficiency of the conversion of laser light to X rays. While this improved symmetry control, the low gas fills led to a faster filling of the hohlraum with plasma. Significant progress was made on reducing effects of engineering features; for example, the fill tube size was reduced five-fold. Fusion yields doubled, to ~55 kJ, with evidence that a significant fraction of the yields arose from self-heating.

Most recently, HYBRID campaigns increased capsule size to increase the energy delivered to the target and optimized both design parameters and capsule quality to improve the symmetry of the implosions. Yields increased again, to almost 200 kJ. On August 8, 2021, a HYBRID-E implosion produced a fusion yield of 1.3 MJ. This corresponds to a gain of 0.7 relative to the incident laser energy of 1.8 MJ and a capsule gain of about 5 (fusion yield relative to the energy absorbed by the capsule). While this achievement is short of ignition as defined in the 1997 NRC study,[1] it is well above the gain of 0.3 milestone

[1] National Research Council, 1997, *Review of the Department of Energy's Inertial Confinement Fusion Program: The National Ignition Facility*, Washington, DC: National Academy Press, https://doi.org/10.17226/5730.

as outlined in the report as the point where "fusion reactions occur over a sufficient region to induce propagation of the thermonuclear burn into the denser, colder, outer fuel."

The August 8th LID shot on NIF provided a convincing demonstration of significant self-heating, reaching temperatures and yields far beyond any previous experiment and unobtainable by compression alone. It offers significant validation of the hot-spot concept for ICF, and detailed data that can be used to test and constrain the complex multi-scale codes used in ICF target design. It also highlights the difficulty of operating in a fundamentally nonlinear regime, where small changes in the initial conditions or drive can lead to large changes in outcome. Clearly, there is much fundamental science that remains to be done.

LASER DIRECT DRIVE

The laser direct-drive (LDD) approach to hot-spot ignition has many similarities to LID, but irradiates a spherical fuel capsule directly with laser photons instead of X rays from a laser-driven hohlraum. (See Figure A.2 for illustration.) This has the advantage of a significant increase of driving energy (on NIF, the laser delivers 1.8 MJ of energy while the hohlraum delivers ~0.2 MJ), which enables much larger capsules, but comes at the cost of introducing a source of direct asymmetry, since the laser beams hit the target surface directly. Further, NIF is presently configured to deliver its laser beams into the poles of a cylindrical hohlraum, and not to the surface of a spherical capsule. Thus, much of present-day LDD research is focused on scaling experiments performed on the 30 kJ Omega laser. In a sense, LID is better for drive homogeneity/smoothing, while LDD is better for efficiency and coupling, potentially, although it is susceptible to different laser plasma instabilities.

The spherical concentric layers of a LDD ICF target typically consist of a central region of DT vapor surrounded by a cryogenic DT-fuel layer and a thin, nominally plastic layer, called the ablator. The incident laser drive is designed to be as spatially uniform as possible on the outer surface of the capsule, using multiple laser beams with a peak, overlapped intensity of $<10^{15}$ watts/cm^2. The intensity of the laser pulse is varied over nanosecond time scales to produce the desired profile of ablation pressure. As with LID, the ablation process causes the target to accelerate and implode via the rocket effect, reaching a peak implosion velocity in the 300 to 500 km/s range, depending on the implosion design. As the implosion proceeds, the laser energy acts on an increasingly small surface and encounters previously ablated material, called coronal plasma, that typically absorbs 60-70 percent of the laser energy. The hydrodynamic efficiency of converting that absorbed laser energy to inward kinetic energy of the shell via the rocket effect is about 9 percent. This gives a conversion efficiency of incident laser energy to shell kinetic energy of about 6 percent for laser direct drive.

As the DT-fuel layer decelerates, the initial DT vapor and the fuel mass that was thermally ablated from the inner surface of the DT-ice layer are compressed and form a central hot-spot plasma having a pressure of ~100 Gbar, in which fusion reactions occur for a few tenths of a nanosecond around stagnation. ICF relies on the 3.5 MeV DT-fusion alpha particles depositing their energy in the hot-spot plasma, causing the hot-spot temperature to rise sharply and a thermonuclear burn wave to propagate out through the surrounding nearly-degenerate, cold dense DT fuel, producing significantly more energy than was used to heat and compress the fuel. If the inertia of the compressed DT shell confines the hot-spot plasma long enough for alpha heating to trigger the ignition instability, the LDD capsule will achieve energy gain. The onset of central-hot-spot ignition is predicted to occur when the product of the temperature and areal density of the hot-spot plasma reach a minimum of 5 keV and 0.3 g/cm^2.

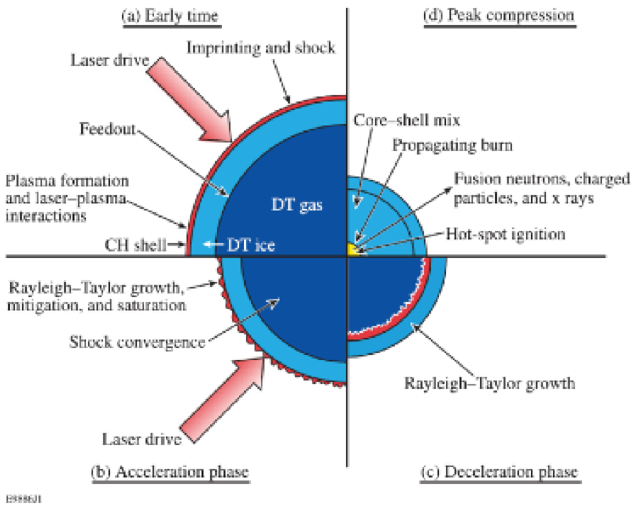

FIGURE A.2 The key target physics for the four stages of central hot-spot ignition in a LDD ICF. SOURCE: R. S. Craxton, K. S. Anderson, T. R. Boehly, et al., 2015, "Direct-drive inertial confinement fusion: A review," Physics of Plasmas 22(1): 110501, https://doi.org/10.1063/1.4934714.

Outlook

Laser direct-drive ICF is studied on the OMEGA laser facility, through both focused experiments to understand the fundamental physics, such as energy coupling, and integrated subscale targets that are designed for ignition on NIF but hydrodynamically scaled to the laser energy available at OMEGA. Hydrodynamic scaling uses a smaller target but maintains critical parameters such as shell convergence, hot-spot pressure, shell adiabat, and implosion velocities, enabling studies of hot-spot formation for spherically symmetric, LDD, DT-layered implosions that scale to burning plasma and ignition designs on MJ-scale lasers in both polar and spherical illumination geometries. (See also Figure A.3.)

A fuel hot-spot pressure in excess of 50 Gbar was demonstrated for direct-drive, layered deuterium-tritium implosions on OMEGA.

The influence of laser plasma interactions on energy coupling and preheat, and the seeding of hydrodynamic instabilities by laser imprint, target imperfections, and engineering features have been investigated on OMEGA and at ignition-relevant scales on the National Ignition Facility.

Low-mode implosion asymmetry has been studied using X-ray imagers and nuclear diagnostics with multiple lines of sight, characterizing the in-flight shell asymmetry and the hot-spot flow velocity at stagnation.

Focused experiments have examined the physics of multi-shock interactions with matter to identify the sensitivity of material release to details of radiation preheat and kinetic effects.

The fusion neutron yield for OMEGA DT cryogenic implosions has been increased by more than a factor of three as guided by statistical modeling of past experiments, thereby achieving an energy-scaled generalized Lawson parameter (defined in Chapter 3) of 0.8 (assuming ~1.35 MJ absorbed energy with 2.0 MJ incident energy) and an extrapolated fusion yield of almost 1 MJ.

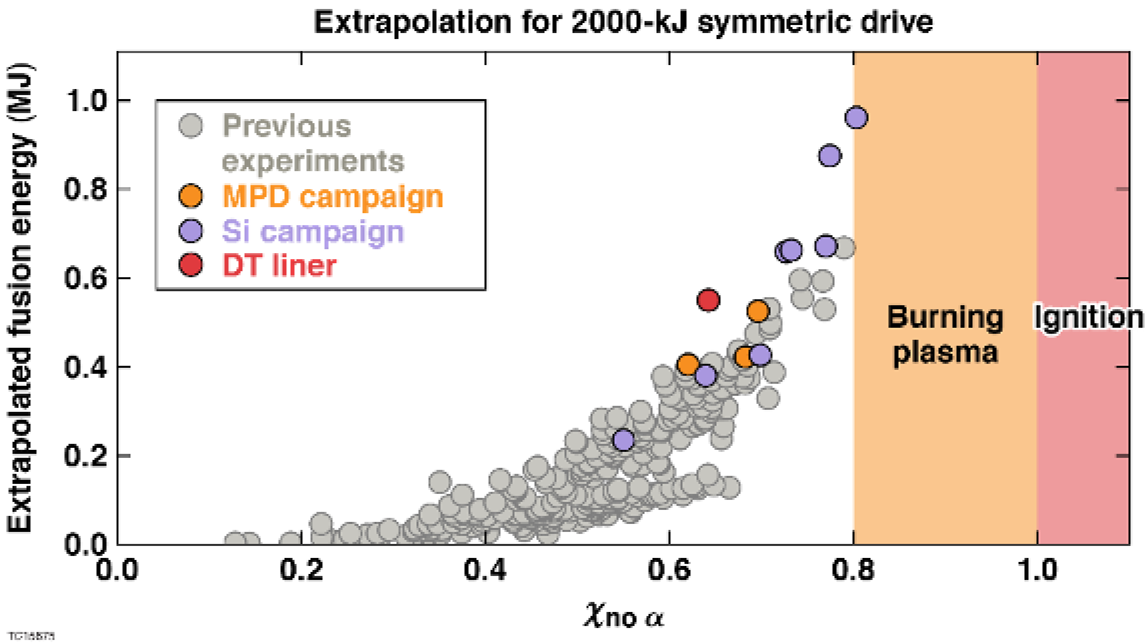

FIGURE A.3 Extrapolated fusion yield at 2 MJ of laser energy for spherical direct drive OMEGA DT cryogenic implosions performed at 0.03 MJ plotted as a function of the energy-scaled generalized Lawson parameter (hot-spot pressure × hot-spot confinement time) is used to quantify the proximity to ignition, where a value of unity corresponds to ignition. Here the pressure and confinement time are estimated without accounting for alpha heating to assess the pure hydrodynamic performance of the implosion. Recent campaigns using Si-doped plastic ablators are approaching the burning plasma regime (i.e., yield amplification due to alpha heating > 3.5) with extrapolated fusion yield of almost 1 MJ. An ignited plasma has a yield amplification due to alpha heating greater than 15-25.
SOURCE: Courtesy of Varchas Gopalaswamy, Laboratory for Laser Energetics of the University of Rochester.

MAGNETIC DIRECT DRIVE AND MAGNETO-INERTIAL FUSION

Magnetic direct drive (MDD) fusion is distinct from the two laser fusion concepts in that the implosive force is provided by the interaction of direct current through a cylindrical target with its own self-generated magnetic field, rather than by photons. Just as parallel currents running along parallel wires will tend to draw two wires together, current running through a cylinder will tend to implode the cylinder, with implosion pressures that increase with the square of the current and the inverse square of the radius. For example, Sandia's Z machine can deliver more than 20 MA of current to a fuel-filled metal cylinder, generating pressures around 1 Gbar at stagnation. Importantly, the pressure on an imploding MDD target increases as long as current flows. This is in contrast to LID and LDD, where pressure decreases along with decreasing surface area.

Two other features distinguish MDD from laser-driven ICF concepts. First, the wall-plug efficiency of MDD tends to be much higher than that of laser drivers. For example, NIF's capacitor banks store ~400 MJ of energy and its laser delivers about 2 MJ to cm-scale LID hohlraums (0.5 percent wall-plug efficiency). The capacitor banks on Z store 20 MJ and deliver about 1 MJ to cm-scale cylindrical MDD targets (~5 percent wall-plug efficiency). Second, the time scales of MDD tend to be longer than that of lasers, with current risetimes of ~100 ns, rather than the ~2 ns of a NIF laser drive. Thus, while the energy density of MDD is comparable to that of NIF, the power density is much lower. Combined with the inherently two-dimensional (cylindrical) compression of MDD—as opposed to the three-dimensional

(spherical) compression of LID and LDD, pulsed power drivers can access distinct target designs and concepts for fusion.

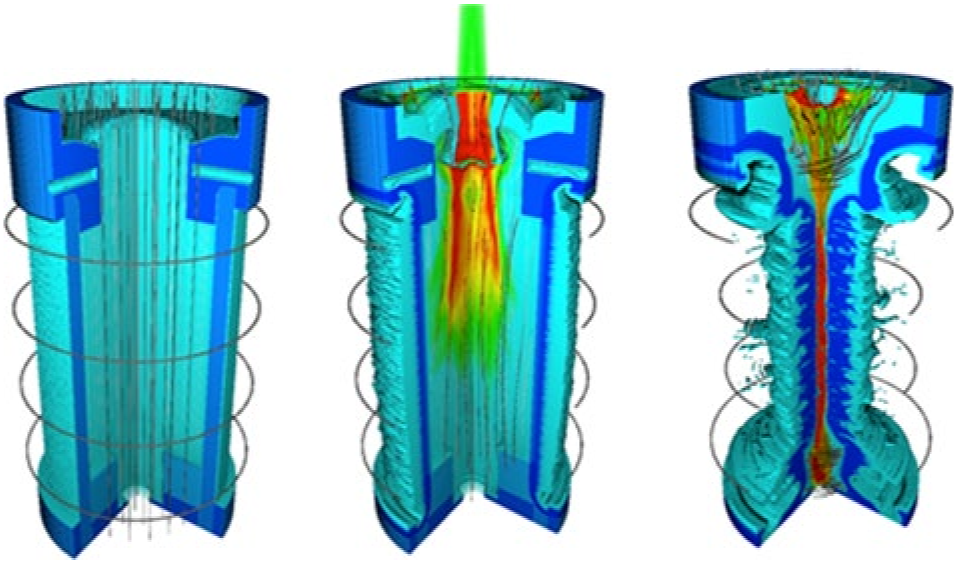

FIGURE A.4 Three stages of a Magnetized Liner Inertial Fusion (MagLIF) experiment: *Left*: a ~1 cm tall beryllium cylinder is filled with fusion fuel (D2), and a ~10-20 T axial magnetic field is introduced by external magnetic field coils (not shown). Center: an axial current runs along the outside of the cylindrical liner, creating a JxB force that begins to implode the liner, fuel, and axial magnetic field; then, a laser is fired into the top of the target, preheating the fuel to temperatures of ~100 eV. The magnetic field inhibits radial heat conduction, keeping the fuel hot during the implosion. Right: an increasing current drives a relatively slow, 100 km/s cylindrical implosion, increasing the fuel temperature to ~3-4 keV, compressing the fuel to ~0.3 g/cm3, and flux-compressing the axial field to ~10-20 kT, producing a stagnating plasma that generates 10^{13} DD fusion neutrons (2kJ DT equivalent) over about 2 ns. Charged fusion products are trapped by the large areal density in the axial direction and by the high magnetic fields in the radial direction. SOURCE: Reprinted "Experimental Demonstration of Fusion-Relevant Conditions in Magnetized Liner Inertial Fusion," with permission from M.R. Gomez, *Physical Review Letters* 113:155003, 2014, https://doi.org/10.1103/PhysRevLett.113.155003. Copyright 2014 by the American Physical Society.

One way to harness the distinct power delivery of MDD is the concept of Magneto-Inertial Fusion (MIF), which operates at pressures of ~1-10 Gbar rather than the ~100-300 Gbar of traditional ICF. Here, the committee notes a target concept called Magnetized Liner Inertial fusion (MagLIF), as depicted in Figure A.4. Where laser ICF uses spherical compression, high power, and high pressure to reach the Lawson (Pt) and confinement (ρR) requirements for self-heating and gain, MIF relies on preheat, external magnetic fields, longer times, and larger volumes to approach those requirements. In particular, MagLIF uses the following ideas for MDD fusion:

- Preheat: Where spherical implosions of a cryogenic target can create multi-keV temperatures at convergence ratios (CR) of about 30 from shock and compressional heating alone, reaching those temperatures with cylindrical compression would require much higher convergence ratios that would exacerbate instabilities. Preheating MagLIF fuel to temperatures of ~100 eV using a ~2 kJ laser pulse enables relatively slow (~100 km/s) implosions that can reach multi-keV temperatures at CR ~30 while preserving the inertial integrity and stability of the imploding cylindrical liner.

- Premagnetization: Where spherical implosions can achieve ρR sufficient to trap the energy from charged fusion products at CR ~30, the fuel ρR in a cylindrical MDD implosion is ~10× smaller than required for inertial confinement. Worse, large preheat temperatures and long (~20 ns) implosion times make conductive heat losses a serious concern for MIF. Introducing an external axial magnetic field before the implosion solves both of these problems: the magnetic field inhibits radial conduction losses, keeping the fuel hot during the implosion, and the initial magnetic field is flux-compressed by the implosion to such a degree that it effectively traps and confines charged fusion products that are emitted in the radial direction. In the axial direction, MDD has sufficient areal density to inertially confine charged fusion products.

Outlook

The MagLIF concept with DD fuel has demonstrated yields above 10^{13} neutrons on Sandia's Z machine, which, due to the ~100× smaller cross section of the DD reaction compared to DT, is equivalent to ~10^{15} DT neutrons, or ~2 kJ of DT fusion energy. This is roughly equivalent to LID experiments at NIF without self-heating. Further, analysis of primary and secondary neutron spectra indicate that ~40 percent of the charged tritons produced in one branch of the DD reaction are confined by the combination of large BR (magnetic radial confinement) and ρZ (axial inertial confinement). It is important to note that a BR sufficient to trap these 1 MeV tritons would also be sufficient to trap the 3.5 MeV alpha particles from DT reactions. However, the demonstrated efficacy of this confinement does not mean that present-day MagLIF targets would have appreciable self-heating, since the stagnation plasmas have ρTau ~20× less than is required for energy deposition that effectively feeds back into the fusing plasma.

While these experiments have demonstrated the fundamental soundness of the MIF concept, there are both practical and physics-based limitations to what can be done with present U.S. pulsed power capabilities. On the practical side, Sandia's Z machine is not an ignition facility: many of its principal components are more than 35 years old, many are becoming less reliable with age, and none were built to handle high yields. Even if the facility could handle high yields, scaling calculations indicate that significantly higher preheat energies (~30 kJ 15X) and implosion currents (~50 MA 3X) are needed to bring the MagLIF concept into the burning plasma regime.

Extensive work has been done to understand and mitigate the risks associated with scaling MDD to larger drivers and targets. The required axial magnetic fields for a burning MagLIF plasma are only 20T and have been demonstrated by existing technology. Experiments using one quad of NIF to preheat fuel-filled cylinders with the required ~30 kJ of laser preheat are ongoing in a cross–lab collaboration. These experiments include novel diagnostics that can detect mix from various target components (mix is a concern for MIF because, unlike conductive heat losses, radiative heat losses from high-Z impurities in the hot fuel are not inhibited by the external magnetic field). Extensive work has been done to understand the sources, evolution, scaling, and mitigation of the magneto-Raleigh-Taylor instability, which can lead to non-uniform and ill-confined stagnation plasmas. Finally, current-scaling studies are under way to anticipate and understand current-loss mechanisms on any potential future driver.

With its relatively low pressures, pulsed power fusion operates in a much less demanding physical regime than laser-driven ICF. With its relatively low power densities and high energy densities, it offers opportunities for robust target concepts that do not require the high finesse of multi-shock spherical compression. And with its high wall-plug efficiency, pulsed power fusion has clear paths to high-gain targets that may offer advantages for fusion energy. It should be noted, however, that pulsed power as a driver technology and MDD as a fusion drive are supported at a relatively modest level in the United States, with a relatively small pool of experts. For example, most U.S. hydrocodes do not include the magneto-hydrodynamics packages that enable MDD target design, and there is a single NNSA Center of Excellence that is devoted to pulsed power science. These resources may be further stressed by the increasing maintenance needs of an aging Z facility (which, in addition to ICF also supports radiation effects, materials properties, and fundamental science experiments) and the absence of a mid-scale (~10 MA) pulsed power

facility in the United States that could advance fundamental pulsed power science and train the next generation of scientists.

B

Tools of HED

This appendix is intended as a brief introduction to the experimental and computational tools of high energy density science, with a summary of capabilities in each case.

EXPERIMENTS

Static Compression

Diamond-anvil cells (Figure B.1)	to 0.1-1 TPa, 10^3-10^4 K (0.1-1 eV) continuous to pulsed heating compression between points of diamonds, arbitrary duration density measured to 0.1-1 percent, pressure to 1-10 percent

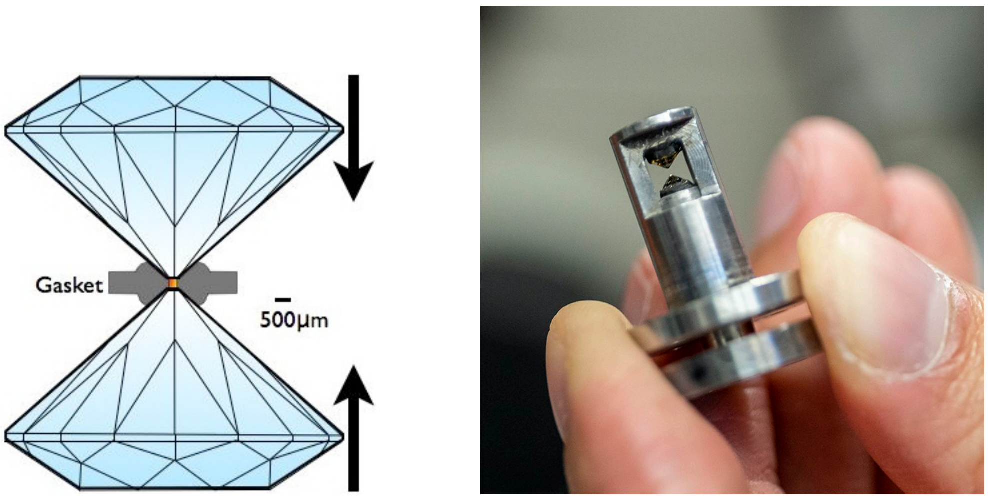

FIGURE B.1 Schematic cross section (*left*) of diamond anvils compressing a sample (*orange*) contained inside a gasket. Samples may be as small as 1-5 µm and as large as 0.5-2 mm across, with thicknesses of about 1 µm-1 mm. Because they are small in size (*right*), diamond-anvil cells can fit inside many instruments, including cooling and heating chambers.
SOURCES: (*Left*) Courtesy of H.P. Scott. (*Right*) Courtesy of N. Yao, Lawrence Berkeley National Laboratory.

Dynamic Compression

Gas-guns (Figure B.2)	to 0.1-1 TPa, 10^4 K (1 eV) range over 0.1-1 µs mechanical impact at up to 1-10 km/s, planar compression shock, multiple-shock, ramp loading density, pressure measured to 0.1-1 percent
Pulsed-power	to 1-2 TPa, 10^4-10^5 K (1-10 eV) range over 0.1-1 µs

(Figure B.3)	mechanical impact to 10 km/s, or magnetic compression (planar) shock, multiple-shock, ramp loading density, pressure measured to 1 percent
	to PPa, 10^7-10^9 K (1-100 keV) range over 10-100 ns magnetic compression (cylindrical shock) density, pressure calculated to 1-10 percent
Laser (Figures B.4-B.6)	Dynamic compression to 100 TPa, 10^7 K range to 100 TPa, 10^5 K (10 eV) range over 10-50 ns shock, multiple shock or ramp loading (planar) pre-compression density, pressure measured to 1 percent
	to 100 TPa, 10^6 K (10 eV) range over 1-10 ns laser shock or ramp (spherical compression) density, pressure measured to 1-10 percent
	to PPa, 10^7-10^9 K (1-100 keV) range over 1-10 ns laser shock (spherical) density, pressure calculated to 5-10 percent

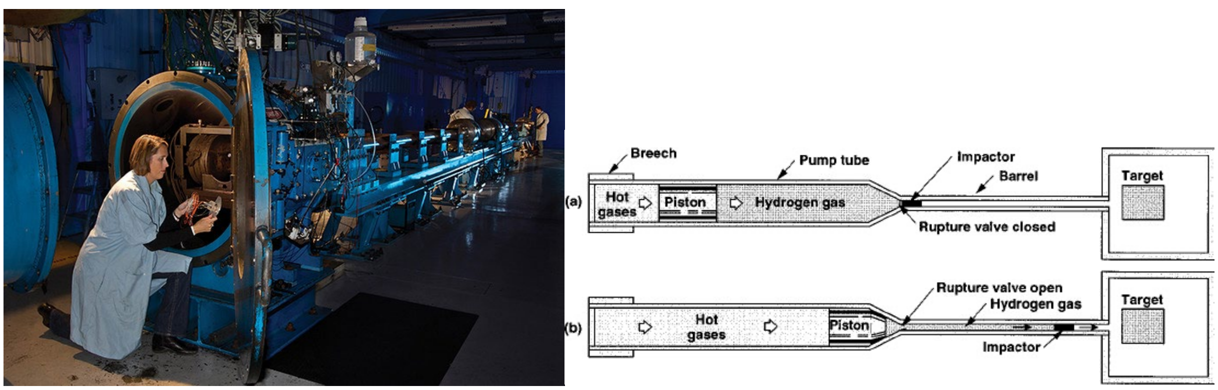

FIGURE B.2 (*Left*) Two-stage light gas gun. (*Right*) Schematic of two-stage light-gas gun in use. Samples are typically mm-cm in size.
SOURCES: (*Left*) Courtesy of Los Alamos National Laboratory. (*Right*) Reprinted “Minimum Metallic Conductivity of Fluid Hydrogen at 140 GPa (1.4 Mbar),” with permission from W.J. Nellis, S. Weir, and A.C. Mitchell, *Physical Review B* 59(5), 1999, http://dx.doi.org/10.1103/PhysRevB.59.3434. Copyright 1999 by the American Physical Society.

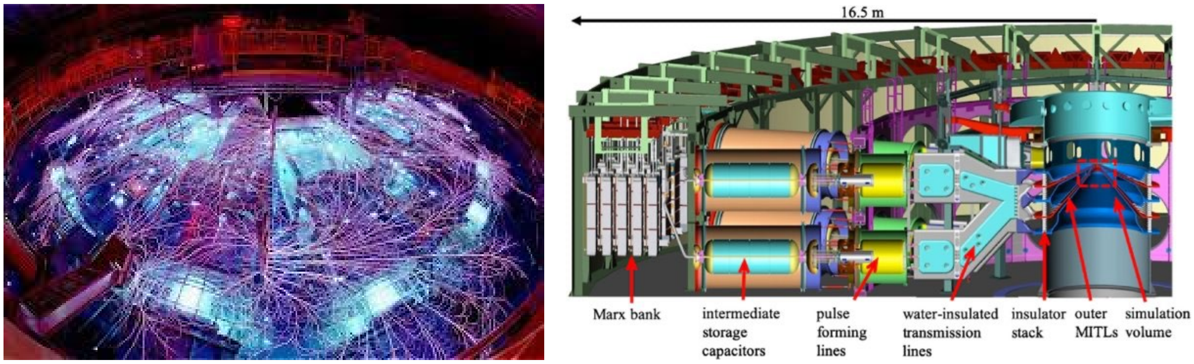

FIGURE B.3 (*Left*) Z pulsed-power facility, shown in action at Sandia National Laboratories, is 33 m (110 ft.) across. (*Right*) Schematic cross section of Z pulsed-power machine, with red dashed square indicating location of the sample assembly at the center of the machine. Samples are typically mm-cm in size.
SOURCES: (*Left*) Courtesy of R. Montoya, Sandia National Laboratories, https://www.flickr.com/photos/departmentofenergy/8056998596. (*Right*) N. Bennett, D.R. Welch, C.A. Jennings, et al., 2019, "Current Transport and Loss Mechanisms in the *Z* Accelerator," *Physical Review Accelerators and Beams* 22:120401. CC BY 4.0.

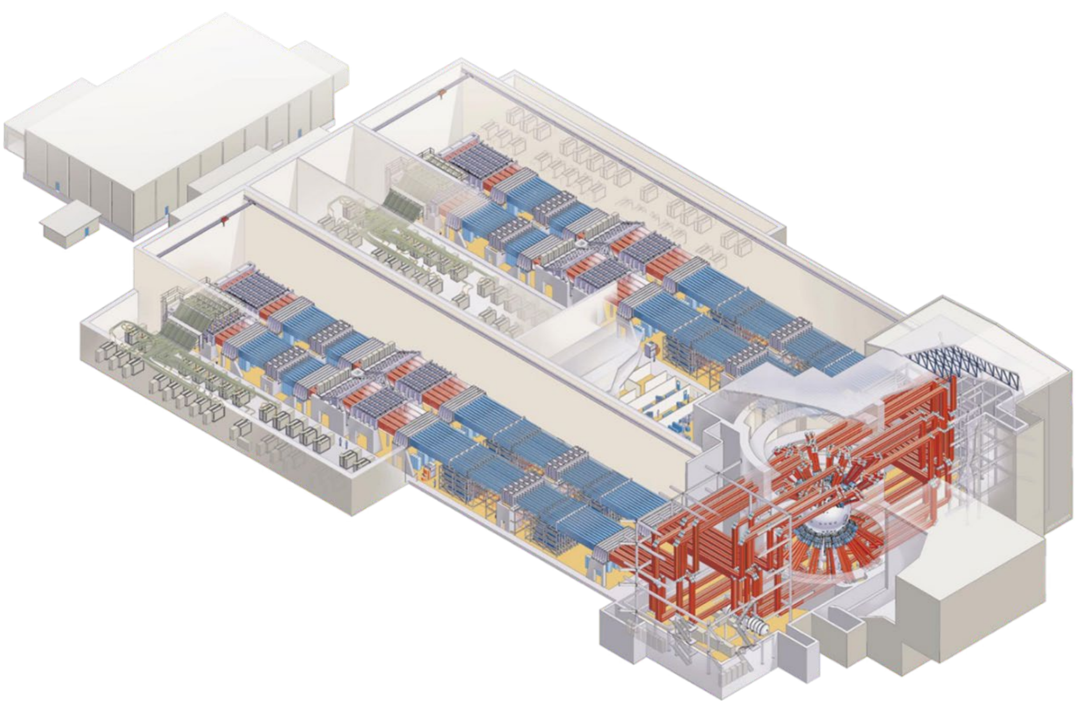

FIGURE B.4 Schematic of the National Ignition Facility at Lawrence Livermore National Laboratory, with light from two laser bays (top and bottom at left) directed into the spherical target chamber (right). The building is larger than 3 football fields placed side-by side.
SOURCE: Wikimedia Commons, https://commons.wikimedia.org/wiki/File:NIF_building_layout.png.

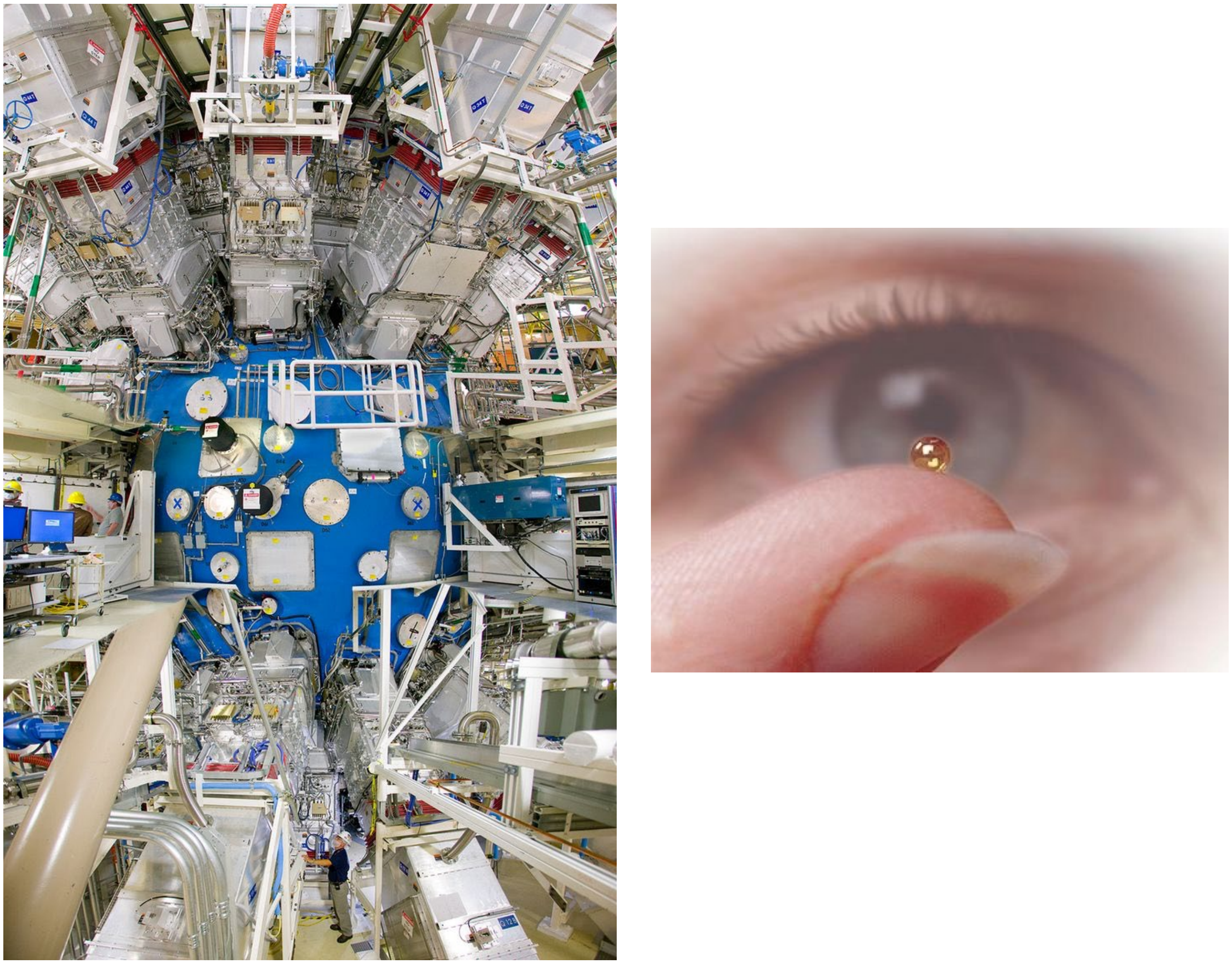

FIGURE B.5 Composite image of the NIF target chamber in blue (*left*), which is 3 stories high (note person for scale at bottom). In contrast, the target for ICF experiments (*right*) is only a few millimeters across. SOURCES: Lawrence Livermore National Laboratory, see (*left*) https://lasers.llnl.gov/about/how-nif-works/target-chamber and (*right*) https://str.llnl.gov/content/pages/past-issues-pdfs/1999.07.pdf.

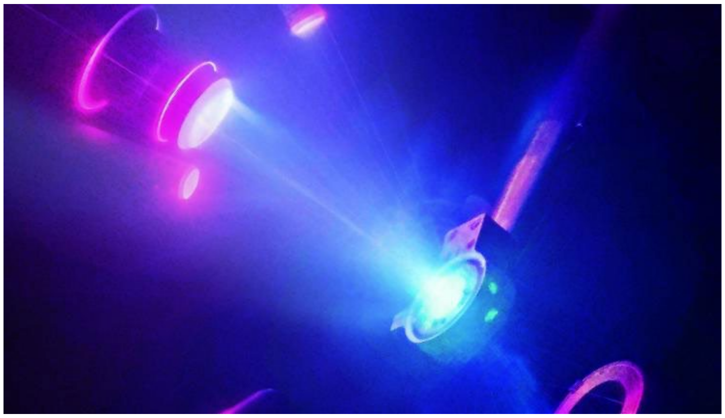

FIGURE B.6 Image of a laser-driven shock-compression experiment at the University of Rochester's Laboratory for Laser Energetics. The target is a diamond-anvil cell that is holding a sample already at high pressures, to be further compressed by the laser-shock.

SOURCE: B. Bishop, 2018, "First Experimental Evidence for Superionic Ice," https://www.llnl.gov/news/first-experimental-evidence-superionic-ice. Image by M. Millot/E. Kowaluk/J.Wickboldt/LLNL/LLE/NIF.

THEORY AND SIMULATIONS

Quantum mechanical simulations
DFT, Pseudopotentials at low/warm T
First Principles MD and Path Integral at warm/high T
Time-dependent DFT
Collisional-radiative non-equilibrium kinetics
Classical molecular dynamics,
Reduced models for turbulence and mix
Particle-in-cell (PIC)
Hybrid fluid-PIC
Maxwell Vlasov Fokker Planck
Laser-plasma interaction
Laser wakefield acceleration
Extended MHD
Radiation transport
Hydrodynamic simulations
Electromagnetic (EM) simulations: optics/radiation/EM-field
Combined Rad/Hydro/MHD simulations
Data-driven simulations: Artificial Intelligence/Machine Learning (AI/ML)

FIGURE B.7 High-performance computers, such as this on at the Los Alamos National Laboratory, support theory, modeling, and simulation in high energy density science.
SOURCE: Los Alamos National Laboratory, "Radical Supercomputing," https://www.lanl.gov/science-innovation/features/radical-supercomputing.php.

C

Examples of High Energy Density Experimental Facilities in the United States

Table C.1 lists examples of several high energy density (HED) science experimental facilities in the United States, along with key characteristics. There are additional facilities, especially at smaller scales, in universities, national laboratories, and other user facilities. This list does not consider computational facilities, which continue to evolve at a rapid pace in national laboratories, industry, and academia.

TABLE C.1 Examples of U.S. High Energy Density Science Facilities

Facility	Machine Type	Energy Delivered	Peak Power	Repetition Rate	Pressure planar/sphere
National Ignition Facility Livermore National Lab	Laser	1.8-MJ UV photons	500 TW	~1 shot/4hr	100 Mbar/ 10 Gbar
The Z-Machine Sandia National Laboratories	Pulsed power	3.5-MJ current	350TW 26 MA	~1 shot/day	10 Mbar/ 100 Mbar
LLE : OMEGA/OMEGA EP University of Rochester	Lasers	30-kJ UV	30 TW	~1 shot/hr	50 Mbar/ 1 Gbar
Linac Coherent Light Source (MEC) Stanford Linear Accelerator	X-ray laser + Laser	1-mJ x rays + 50-J green	10 GW	120 Hz	5 Mbar
Advanced Photon Source (DCS) Argonne National Lab	Synchro-tron + Laser	1-mJ x rays + 100-J UV	10 MW	120 Hz	10 Mbar

(MEC = Matter at Extreme Conditions End Station, DCS = Dynamic Compression Sector)

D

List of All Report Recommendations

LEADING RECOMMENDATIONS

Leading Recommendation: To strengthen its global leadership in high energy density (HED) science and address future national needs, the NNSA should exploit and enhance the capabilities of its flagship HED facilities (e.g., the National Ignition Facility, Z Pulsed Power Facility, and Omega Laser Facility) by establishing plans over the next 5 years for (1) extending, upgrading, or replacing those facilities; (2) increasing the promotion of forefront technology development, including in high-intensity lasers; (3) enhancing academic capabilities and mid-scale facilities; and (4) broadening remote access to its major experimental and computing facilities.

Leading Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should (1) broaden its current programs for achieving excellence through diversity, equity, and inclusion while improving workplace climate and (2) develop a strategic plan for balancing security and proliferation concerns with openness and accessibility, such as for collaborators internationally, and with academia and the private sector.

MAJOR RECOMMENDATIONS

Major Recommendation: The NNSA should work with the academic and national laboratory user community, relevant government agencies, and industry to develop a high-performance computing (HPC) strategy for high energy density science over the next 2 years. This strategy should include benchmarking and the verification and validation of codes, code comparisons, the close integration of simulations using HPC with experiments, co-development of hardware and software for the research community, open-source documentation of codes and experimental results in a standardized open format (e.g., to enhance use and effectiveness of machine learning and artificial intelligence tools), and an industry-relevant implementation plan.

Major Recommendation: The NNSA and the national laboratories should, in coordination with partner science agencies (e.g., including the Department of Energy's Office of Science and the National Science Foundation), academia, and industry, set expectations for rigorous benchmark experiments that can provide solid foundations for multi-scale high energy density simulations. Particular emphasis should be given to characterizing material properties under extreme and non-equilibrium conditions, including conditions accessible at university- and mid-scale facilities, and develop a new generation of diagnostics that can take advantage of modern technology such as higher repetition rate (e.g., compact light sources) that access a range of time and length scales.

Major Recommendation: The inertial confinement fusion community should redouble efforts to focus on the underlying basic science to (1) achieve robust ignition and the maximum yield with optimal efficiency, (2) establish the best uses of laboratory burning plasmas, and (3) help identify the best path for future experimental and computational facilities. In particular, the sustainment of innovation and breakthrough research will require a careful balance between yield-producing and non-ignition experiments. Additionally, the NNSA should work with the relevant agencies (e.g., the

Department of Energy's Fusion Energy Sciences and Advanced Research Projects Agency–Energy and the National Science Foundation) and private industry to leverage research in inertial fusion energy and—where possible—partner in research areas of mutual interest.

RECOMMENDATIONS

Recommendation: The NNSA should take steps to enable institutions working on high energy density research to (1) assess the climate; (2) get help from subject-matter experts to make explicit and quantifiable diversity, equity, inclusion, and accessibility (DEIA) goals; and (3) implement and ensure achievement of these DEIA goals.

Recommendation: The NNSA should support more internships, postdoctoral opportunities, faculty visitorships, and early career programs in high energy density science, coordinating across the NNSA in a manner similar to that supported by the Department of Energy's Office of Science.

Recommendation: The NNSA should provide explicit support and recognition for national laboratory scientists to increase collaborations, mentorship, and outreach with the fundamental research community, in order to build public excitement and the future workforce. Examples include joint appointments or sabbatical opportunities and travel/lectureship programs that partner with minority-serving institutions and the public at large.

Recommendation: The NNSA should periodically assess and, where possible, reduce barriers to university collaborations—for example, by formally recognizing the importance of, and therefore supporting and rewarding, laboratory staff engaged in effective collaborations.

Recommendation: NNSA laboratories should enforce concrete policies for accountability around intolerable, unacceptable behaviors.

Recommendation: In addition to training Ph.D. scientists, NNSA laboratories should invest in educational (apprenticeship) programs at institutions for training of technicians and technical staff at the bachelor's or master's level, doing so in line with the laboratories' diversity, equity, inclusion, and accessibility goals.

Recommendation: NNSA national laboratories should promote collaborations with academia by sharing data related to unclassified research (in consistent data format) and providing open/educational versions of their computational codes.

Recommendation: The NNSA should collaboratively develop industry-relevant technical roadmaps for critical capabilities in computation, diagnostics, and targets and provide more—and more frequent—funding opportunities for industry to provide these capabilities.

Recommendation: To strengthen its global leadership in high energy density science and address future national needs, the NNSA should increase the promotion of forefront technology development, and in particular take the necessary steps to achieve ultra-high power laser capabilities on par with what is being developed around the world.

Recommendation: To enhance career pathways for high energy density science research at NNSA facilities, the NNSA should promote international collaborations and increase remote access to those facilities.

E

Committee Activities

PUBLIC COMMITTEE MEETINGS

May 19, 2021 – Virtual Meeting

11:15 am ET	Discussion with congressional staff- SASC, HASC
11:45 am ET	Discussion with NNSA - Njema Frasier, Paul Davis, and Ann Satsangi
12:30 pm ET	Additional discussion / Q&A

June 24, 2021 – Virtual Meeting

3:00 pm ET	Plasma 2020 briefing - Mark Kushner, and Gail Glendinning
3:30 pm ET	AMO2020 briefing - Jun Ye, Nergis Mavalvala, and Lou DiMauro

October 4, 2021 – Virtual Meeting

12:05 pm ET	Discussion with Panel 1: DEI Ed Thomas, Royce W. James, Nicholas Murphy, Arturo Dominguez, and Elizabeth Merritt *Moderator*: Felicie Albert
2:15 pm ET	Discussion with Panel 2: HPC/ML/AI Thomas Mattson, Frank Graziani, Eric Schwegler, and Dimitri Kusnezov *Moderator*: David Ceperley

October 5, 2021 – Virtual Meeting

12:05 pm ET	Discussion with Panel 3: Industry Mario Manuel, John Cary, Rob Littlewood, and Mahadevan Krishnan *Moderator*: Franklin Dollar

CLOSED-SESSION COMMITTEE DELIBERATIONS

The committee met in closed session a total of 33 times. These sessions include five full committee meetings. Meeting one was held virtually on non-contiguous dates in May 2021 on the 11th, 19th, and 21st. Meeting two (virtual) was on June 24, 2021. Meeting three (virtual) was on August 3, 2021. Meeting four (virtual) was on October 4-5, 2021. The final full meeting was on April 25-26, 2022. All other closed-session meetings of the committee (28 instances) were 1-hour virtual meetings held on a near-weekly basis between October 20, 2021, and June 6, 2022.

SITE VISITS OF HIGH ENERGY DENSITY SCIENCE NATIONAL LABORATORIES

The committee engaged with each laboratory's senior leadership, receiving an overview briefing of the organization and work. The committee discussed with relevant technical staff the answers to questions that had been submitted prior to the site visits. (See Appendix F.) Finally, committee held virtual breakout groups focused on different aspects of the laboratory staff: Technical Staff, Scientific Staff, Post-Docs Staff, Early Career Staff, and Education, Recruitment, and Outreach.

- **Stanford Linear Accelerator Center (SLAC) / Linac Coherent Light Source (LCLS), California**
  August 20, 2021

- **Sandia National Laboratory / Z Pulsed Power Facility, New Mexico**
  August 23, 2021

- **Laboratory for Laser Energetics (LLE) / Omega Laser Facility, New York**
  August 26, 2021

- **Lawrence Livermore National Laboratory (LLNL) / National Ignition Facility (NIF), California**
  September 3, 2021

- **Los Alamos National Laboratory (LANL), New Mexico**
  September 22, 2021

ADDITIONAL INPUT-GATHERING SESSIONS

Town Halls – August 11 and 16, 2021

Town halls were held to present the study to members of the high energy density (HED) science community and interested public. The study committee sought input from the research community on areas of scientific interest, potential new directions, and workforce/funding issues.

Student Listening Sessions – September 13, 14, and 17, 2021

The committee invited students and recent graduates for informal conversations about the key concerns, challenges, and successes that students face in the current educational pipeline.

Meeting with Asian High-Energy Laser Researchers – October 25, 2021

The committee held a discussion with Asian high-intensity laser researchers to help fulfill its task to assess the state of international high energy density science research. The committee met with:

- Tetsuya Kawachi, National Institutes for Quantum Science and Technology, Japan
- G. Ravindra Kumar, Tata Institute of Fundamental Research, India
- Wenpeng Wang, Shanghai Institute of Optics and Fine Mechanics, China
- Chang Hee Nam, Gwangju Institute of Science and Technology, South Korea

Meeting with the French Alternative Energies and Atomic Energy Commission and Also the Laser Mégajoule Facility – October 28, 2021

The committee held a discussion with Erik Lefebvre of the French Alternative Energies and Atomic Energy Commission and also the Laser Mégajoule facility. This discussion was part of the committee's effort to satisfy the item in its statement of task that calls for an assessment of high energy density science research around the world.

F

Requests Sent to National Laboratories

GENERAL REQUESTS

1. What are some highlights of HED science and ICF at your facility? What do you see as the big questions and opportunities in the field?
    a. List of programs that are relevant to HED science at the site (e.g. ICF, discovery science, other), and what do they support (stockpile stewardship only or other areas/missions)?
    b. Who is in charge of what, how are things organized and why (past and present)?
    c. How are the different programs at the site are related (or not) to each other?
    d. Overview of facilities/resources that support these programs (NIF, computing, target fab, etc.)?
    e. Overview of what has been done over the past 10 years?
    f. Overview of the short (< 5 years), medium (5-10 years), and long-term (> 10 years) goals/plan and foreseen challenges for those plans?

2. What work do you have under way, and what needs do you have, regarding theory, computation, modeling, and simulation? What work are you doing with data science, artificial intelligence, and machine learning?

3. What are you currently doing with diagnostic methods and instrumentation, and what future capabilities would be helpful to you if developed?

4. What new target fabrication capabilities would be helpful to you, <u>bearing in mind all of input to the committee must be publicly releasable</u>?

5. What are your principal concerns about existing and future driver technologies and facility operations?

6. Are there any workforce development items you'd like to share with the committee?
    a. What is the structure of your most effective university partnerships?
    b. How are you working to ensure the pipeline of future HED scientists?
    c. How are you engaging across the pipeline from high school students up to graduate students, e.g., undergraduate internships and graduate fellowships?
    d. How are you addressing diversity, equity, and inclusion?
    e. What are your collaborations with other sites and academia?
    f. Workforce statistics at the institution?

7. Are there any other things that you would like to address, e.g.:
    a. Policy matters related to our statement of task?
    b. International HED science efforts?
    c. Any gaps identified by management (could be workforce, but also resources, scientific/technical). What would you like us to accomplish with this committee (I think we should not be afraid to ask bold questions!)?
    d. Some science highlights, scientific recognition of staff and/or work being done at the site?

G

Committee Biographies

GIULIA GALLI (NAS), *Co-Chair*, is the Liew Family Professor of Electronic Structure and Simulations in the Pritzker School of Molecular Engineering and Professor of Chemistry at The University of Chicago. She also holds a Senior Scientist position at Argonne National Laboratory, where she is the director of the Midwest Integrated Center for Computational Materials. Prior to joining The University of Chicago, she was a professor of chemistry and physics at the University of California, Davis (2005-2013), and the head of the Quantum Simulations group at Lawrence Livermore National Laboratory (LLNL, 1998-2005). She holds a Ph.D. in physics from the International School of Advanced Studies in Italy.

RAYMOND JEANLOZ (NAS), *Co-Chair*, is a professor of Earth and planetary science and astronomy at the University of California, Berkeley, and an Annenberg Distinguished Visiting Fellow at the Hoover Institution. In addition to his scientific research on the evolution of planetary interiors and properties of materials at high pressures, he works at the interface between science and policy in areas related to national and international security, resources and the environment, and education. He chairs the National Academies of Sciences, Engineering, and Medicine's Committee on International Security and Arms Control; is a member of the JASON group that provides technical advice to the U.S. government; has served on the Secretary of State's International Security Advisory Board; and is the past chair of the National Academies' Board on Earth Sciences and Resources. He holds a Ph.D. from the California Institute of Technology.

FÉLICIE ALBERT is the deputy director of LLNL's High Energy Density Science Center and Jupiter Laser Facility, and a research scientist in LLNL's National Ignition Facility and Photon Science Directorate. Her areas of expertise include the generation and applications of novel sources of electrons, X rays, and gamma rays through laser-plasma interaction, laser-wakefield acceleration, and Compton scattering for applications in high energy density (HED) science and warm dense matter studies. She has conducted many experiments using high-intensity and high-energy lasers at various facilities around the world including the National Ignition Facility, the OMEGA Laser, and the LCLS X-ray free electron laser. She received the Presidential Early Career Award for Scientists and Engineers (PECASE) in 2019, and a 2016 Department of Energy (DOE) Early Career Research Program Award to develop new x-ray sources for HED science experiments. She received the 2017 American Physical Society's Division of Plasma Physics (APS-DPP) Katherine E. Weimer Award for outstanding contributions to plasma science research and the 2017 Edouard Fabre Prize for contributions to the physics of laser-produced plasmas. She is a senior member of the Optical Society of America, and a Fellow of the APS-DPP. She earned her Ph.D. in physics from Ecole Polytechnique, France. She is a member of the International Committee on Ultra Intense Lasers (ICUIL), served as chair of LaserNetUS in 2020-2022, and is on the organizing committee of the National Academy of Sciences' (NAS's) Annual Kavli Frontiers of Science Symposium.

DAVID CEPERLEY (NAS) is professor of physics at the University of Illinois at Urbana-Champaign. Early in his career he was employed at LLNL. He was one of the developers of methods to simulate quantum many-body systems such as the electron gas, liquid helium, and dense hydrogen. He is a member of the NAS. He previously served as a member of the National Academies' evaluation of the National Science Foundation's (NSF's) Materials Research Centers.

GILBERT "RIP" W. COLLINS is the Tracy Hyde Harris Professor of Mechanical Engineering and Physics and Astronomy; the associate director of the Laboratory for Laser Energetics; and the director of the Center

for Matter at Atomic Pressures, a Physics Frontier Center funded by NSF, at the University of Rochester. He explores extreme states and processes of matter from thermonuclear burning plasma to dense quantum materials. From 1989 to 2016, he was with LLNL as a staff physicist (1989-1995), group leader for Hydrogen Research (1995-2005), project leader for Implosions and Hydrodynamics (1997-2006), group leader for High Energy Density Shock Physics (2002-2016), associate division leader for Physics (2011-2016), director for the Center for High Energy Density Physics (2015-2016), and distinguished member of the technical staff (2014-2016). He received his Ph.D. in physics from The Ohio State University in 1989. He is working to develop a HED science curriculum, holds a visiting scientist position at LLNL and visiting professorships at The University of Edinburgh and Oxford University, United Kingdom. He has contributed to several decadal, Basic Research Needs, and Advisory Reports sponsored by NSF's Office of Science and the National Nuclear Security Administration (NNSA).

FRANKLIN J. DOLLAR is an associate professor in the Department of Physics and Astronomy and the associate dean of graduate studies in the School of Physical Sciences at the University of California, Irvine, and an enrolled member of the Dry Creek Band of Pomo Indians. His research interests involve laser plasma interactions with ultrafast laser systems, performing high-intensity laser experiments with near and above critical density plasmas for tabletop particle acceleration and the generation of soft and hard x-rays; and the simulation of such experiments using numerical modeling. He is involved with a variety of recruitment and retention efforts for underrepresented students in the science, technology, engineering, and mathematics (STEM) fields, with a particular focus on American Indians. He serves on numerous committees including the Department of Energy's LaserNetUS Scientific Advisory Board, the Fusion Energy Science Advisory Committee, and the executive steering committee for the University of California Leadership & Excellence Through Advanced Degrees program. He is a Kavli Fellow, a Sloan Research Fellow, and a Fellow of the American Physical Society. He is an awardee of the NSF CAREER award, the Tom Angell Faculty Mentorship Award, and the American Indian Science & Engineering Society's Most Promising Scientist Award.

NATHANIEL J. FISCH is a professor of astrophysical sciences in the Department of Astrophysical Sciences and the director of the Program in Plasma Physics at Princeton University. He is also the associate director for academic affairs at the Princeton Plasma Physics Laboratory and an associated faculty in the Department of Mechanical and Aerospace Engineering at Princeton University. Dr. Fisch predicted new ways to control plasma, including methods of generating electrical current in plasma using electromagnetic waves. He also predicted plasma-based methods of achieving the next generation of laser intensities. His current research interests include plasma applications to nuclear fusion, lasers, propulsion, nuclear waste remediation, and astrophysics. Dr. Fisch is a recipient of a Guggenheim Fellowship, the APS Award for Excellence in Plasma Physics, the DOE Bronze Medal for Outstanding Mentor, the Ernest Orlando Lawrence Award, the James Clerk Maxwell Prize for Plasma Physics, the European Physical Society Hannes Alfven Prize, and the Fusion Power Associates Distinguished Career Award. He is a fellow of the APS and the NASA Institute for Advanced Concepts. He earned his Ph.D. in electrical engineering and computer science from the Massachusetts Institute of Technology (MIT). He served as a member on the National Academies' Board of Physics and Astronomy and as the chair of the APS-DPP.

STEPHANIE HANSEN is a Senior Scientist in the Pulsed Power Sciences Center at Sandia National Laboratories, where she studies the atomic-scale behavior of atoms in extreme environments and develops atomic, spectroscopic, equation-of-state, and transport models to help predict and diagnose the behavior of HED plasmas. She is the author and developer of the SCRAM non-LTE spectroscopic modeling code and MUZE, a self-consistent field code used for equation-of-state, scattering, and transport calculations. She received an early-career grant from DOE's Office of Fusion Energy Sciences in 2014, was awarded the Presidential Early Career Award for Scientists and Engineers in 2017, and was elected a Fellow of the APS-DPP in 2019. She holds degrees in physics and philosophy from the University of Nevada, Reno, and has been a visiting associate professor at Cornell University since 2012.

RUSSELL J. HEMLEY (NAS) holds the position of Distinguished Chair in the Natural Sciences and professor of physics and chemistry at the University of Illinois Chicago. His research explores the behavior of matter and materials in extreme environments, notably high pressures and temperatures, and he has co-authored approximately 670 scientific publications. He received his B.A. from Wesleyan University and M.A. and Ph.D. from Harvard University, all in chemistry. Previously, he worked at the Carnegie Institution and has held positions at LLNL, Cornell University, and The George Washington University. He is a member of the NAS, Fellow of the American Academy of Arts and Sciences, Corresponding Fellow of the Royal Society of Edinburgh, Honoris Causa Professor of the Russian Academy of Sciences, and a recipient of the Balzan Prize and Percy W. Bridgman Award, among other honors. He has directed national materials science centers funded by DOE and the Department of Defense (DoD), and has served on numerous DOE, DoD, and National Academies committees.

CAROLYN C. KURANZ is an associate professor of plasma science and engineering in the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan (UM). At UM, Dr. Kuranz has led experimental research in HED science at high-energy laser and pulsed power facilities. Her research interests include HED hydrodynamic instabilities, radiation hydrodynamics, and magnetized plasmas. She is the recipient of National Ignition Facility Photon Science Award, the American Astronomical Society Laboratory Astrophysics Division Early Career Award, and APS Fellowship. She earned her Ph.D. in applied physics from UM. She served as a co-chair of the Fusion Energy Science Community Planning Process. Dr. Kuranz is also an ex officio member of the APS-DPP Executive Committee.

CHARLES F. MCMILLAN was the 10th director of Los Alamos National Laboratory and President of Los Alamos National Security, LLC, from June 2011 to December 2017. During his appointment, Dr. McMillan guided Los Alamos through continuing high levels of mission execution. He signed seven annual assessment reports to the president and Congress evaluating the Los Alamos–designed weapons in the stockpile. Under Dr. McMillan's leadership, the laboratory continued to innovate new techniques and tools to ensure that nation's deterrent remained safe, reliable, and effective. In retirement, Dr. McMillan continues to serve the national security enterprise on various boards and review committees. Prior to becoming laboratory director, Dr. McMillan served as the principal associate director for weapons programs. He was responsible for the science, technology, engineering, and infrastructure enabling the laboratory to fulfill its nuclear deterrent mission. Dr. McMillan directed research that supported the technical analysis necessary to ensure stockpile safety, security, and effectiveness. This included small-scale materials experiments through fully integrated hydrotests that provided essential modeling and simulation data necessary for validation in the absence of full-scale nuclear testing. Dr. McMillan has more than 30 years of scientific and leadership experience in weapons science, stockpile certification, experimental physics, and computational science. He began his career as an experimental physicist at LLNL in 1983, where he held a variety of research and management positions for two decades. He holds a doctorate in physics from MIT and a bachelor's degree in mathematics and physics from Washington Adventist University. He has earned two DOE Awards of Excellence for his work in developing an innovative holographic tool that enhanced the ability of scientists to predict nuclear performance. He is a frequent speaker on the vital role of national laboratories for the nation and the importance of STEM education in cultivating the talent necessary to sustaining that role in the future.

SEKAZI K. MTINGWA is an administrative judge with the U.S. Nuclear Regulatory Commission. He also is a principal partner at TriSEED Consultants, LLC, in Hillsborough, North Carolina, which provides consulting services in STEM, education, and economic development. Dr. Mtingwa played an important role in the design and construction of accelerator systems at Fermilab that were used in the discovery of the top quark. He co-founded the National Society of Black Physicists and the National Society of Hispanic Physicists. Internationally, he co-founded a number of organizations, including the African Laser Centre, which is a network of over 30 laser laboratories throughout Africa and for which he wrote the Strategy and

Business Plan; African Physical Society; Mwalimu Julius K. Nyerere University of Agriculture and Technology in Tanzania, for which he contributed to the design; African Institute for Mathematical Sciences in Ghana; African Light Source Foundation, for which he served as the deputy chair; Lightsources for Africa, the Americas, Asia, Middle East, and Pacific, which seeks to enhance synchrotron light source and crystallography sciences in developing countries, for which he chairs the Executive Committee; and African Review of Physics. He chaired the writing of the Strategic Plan for South Africa's synchrotron light source user community, resulting in South Africa becoming an associate member in 2013 of the European Synchrotron Radiation Facility. Dr. Mtingwa serves as the president of the Interdisciplinary Consortium for Research and Educational Access in Science and Engineering, which seeks to increase the utilization of research facilities at the national laboratories by faculty and students from African-, Latino-, and Native-American Serving Institutions. He is associate member and former chair of the International Union of Pure and Applied Physics C13 Commission on Physics for Development. Dr. Mtingwa retired as a professor of physics at North Carolina A&T State University, and spent several years as the Martin Luther King, Jr. Visiting Professor of Physics and Senior Lecturer at MIT. He is a Fellow of the APS, the American Association for the Advancement of Science, and the National Society of Black Physicists. Dr. Mtingwa is the co-recipient with Anton Piwinski of the Deutsches Elektronen-synchrotron and James Bjorken of Stanford University of the APS 2017 Robert R. Wilson Prize for Achievement in the Physics of Particle Accelerators for the detailed theoretical description of intrabeam scattering. This phenomenon sets ultimate limitations on the performance of a wide class of accelerators, including synchrotron light sources, electron damping rings, and hadron colliders. Their work played a crucial role in the discovery of the top quark at Fermilab and the Higgs boson at CERN's Large Hadron Collider. By receiving the Wilson Prize, Dr. Mtingwa became the first African American to be awarded an APS prize, which is the society's highest category of honors. Dr. Mtingwa received the 2015 Distinguished Service Award from the American Nuclear Society for chairing a 2008 APS study on 21st-century nuclear workforce needs. That study was an important influence leading to the DOE's decision to allocate 20 percent of its nuclear fuel cycle research and development budget to university programs. For his work on mentoring generations of students, faculty, and administrators, Dr. Mtingwa received the 2017 U.S. Presidential Award for Excellence in Science, Mathematics and Engineering Mentoring. Dr. Mtingwa earned a Ph.D. in physics from Princeton University in 1976.

DONNA STRICKLAND (NAS) received her B.Eng. in engineering physics from McMaster University in 1981. She graduated from the University of Rochester in 1989 with a Ph.D. in optics. From 1988 to 1991, Dr. Strickland was a research associate at the National Research Council of Canada. From 1991 to 1992, she was a physicist with the laser division of LLNL. In 1992, she became a member of the technical staff of Princeton's Advanced Technology Center for Photonics and Opto-electronic Materials. Dr. Strickland joined the Department of Physics and Astronomy of the University of Waterloo as an assistant professor in January 1997. She was promoted to full professor in 2018. Her current research interests include ultrafast laser development and nonlinear optics. Along with her Ph.D. supervisor, Dr. Gerard Mourou, Dr. Strickland shared half the 2018 Nobel Prize in Physics for inventing chirped pulse amplification (CPA), which made it possible to amplify ultra-short pulses to unprecedented levels. Dr. Strickland is a Companion of the Order of Canada. She is an Honourary Fellow of the Canadian Academy of Engineering and a Fellow of the Royal Society of Canada. She is also a Fellow of the Royal Society, an Honourary Fellow of the Institute of Physics (United Kingdom), and an international member of the NAS.